APPLYING PRODUCT DESIGN AND DIGITAL CONSTRUCTION METHODOLOGIES TO CONCEPTUALIZE MODULAR AND DISTRIBUTED HEALTHCARE FACILITIES

Master's Thesis Submitted to Aalto University

Aalto University
School of Engineering

Ehsan Ghazanfari
May, 2016

Aalto University
School of Engineering

Aalto University, P.O. BOX 11000, 00076 AALTO
www.aalto.fi

Abstract of master's thesis

Author Ehsan Ghazanfari

Title of thesis Applying Product Design and Digital Construction Methodologies to Conceptualize Modular and Distributed Healthcare Facilities

Degree programme Structural Engineering

Major/minor Structural Engineering/Construction Management **Code** Rak 43

Thesis supervisor Professor Vishal Singh

Thesis advisor(s) Mehmet Yalcinkaya

Date 21.05.2016 **Number of pages** 111 **Language** English

Abstract

In this thesis, conceptual explorations in the design of modular smart health care facilities have been sought for. A new approach towards the modular design of distantly connected built environments has been introduced that can serve to improve the quality of health care services. The results of this research led to developing a new concept for an engineering product that can have diverse use cases. The proposed healthcare unit concept can be used as a single patient room in hospitals or in patient's home and can create a compactable, clean, sanitized, customized, and relaxing space for patients or for the elderly who need special care, making it possible to monitor their status and vital signals remotely and helping to reduce infection rates in hospitals. The user requirements for the product, the product design and development methods, manufacturing methods, and management and lifecycle issues were considered during the concept design. In the course of design, while many established product development and engineering design methodologies were used, new engineering design methodologies were also developed for measuring resource effectiveness of the design solutions. The newly developed measures can be utilized in a variety of design practices. The validity of the newly introduced methodologies was checked with the designed product as a case study and with the help of workshops and other case studies. This thesis can be looked into as a sample of a systematic design decision making for designing buildings and structures and the results of such a design can be a revolutionary view towards connected modular facilities. Engineering design principles such as Structure Sharing, Affordance, Prototyping, Design Engineering, QFD Analysis, Modularization, etc. and design and manufacturing technologies such as Direct Digital Manufacturing (DDM), 3D Printing, CNC Laser Cutting, CAD and 3D Modeling, MCAD and Simulations, Rendering and Visualizations, Virtual Reality (VR), etc. were reviewed and utilized in the course of this Master's thesis.

Keywords Modular health care facilities, distributed distant units, QFD, structure sharing, affordance, design engineering, direct digital manufacturing, 3D modelling, 3D printing, virtual reality.

Table of Contents

Table of Figures

Table of Tables

List of Abbreviations and Symbols

Abbreviations:

DDM	Direct Digital Manufacturing
BIM	Building Information Modeling
HaH	Hospital at Home
HCAI	Healthcare associated infections
PLM	Product Lifecycle Management
CAD	Computer Aided Design
MCAD	Mechanical Computer Aided Design
API	Application Programming Interface
QFD	Quality Function Deployment
CNC	Computer Numerical Control
ADDLab	Aalto Digital Design Laboratory
VDC	Virtual Design and Construction
MRSA	Methicillin Resistant Staphylococcus Aureus
VRE	Vancomycin Resistant Enterococcus
ESBL	Extended-Spectrum beta-Lactamase
CPE	Carbapenemase-producing Enterobacteriaceae
RSV	Respiratory Syncytial Virus
HEPA	High-Efficiency Particular Air
FM Tree	Function Means Tree
VR	Virtual Reality
IOT	Internet of Things
WHO	World Health Organization
EBD	Evidence-Based Design
CFCs	Chlorofluorocarbons

Symbols:

SS	Structure Sharing
RE	Resource Effectiveness
Adm	Admissibility of Structure Sharing
S	Number of Structures
NNE	Number of Negative Effects
RI	Relative Importance
RQOF	Relative Quality of Function

Acknowledgements

I wish to express my gratitude to Professor V. Singh for supervising this research and providing financial support from Aalto University M.Sc. thesis grants.

I would like to thank all the experts and other individuals who willingly allocated their time to support the developments made in this research.

Finally, I must acknowledge the efforts of the staff at the department of Civil and Structural Engineering at Aalto University and ADDLab for creating a calm working environment and providing laboratory facilities to researchers.

CHAPTER 1: Introduction

Scope of the Thesis

Improving the Engineering Design of Health Care Facilities

This thesis, introduces a new way of thinking in the design stage towards the improvement of health care facilities. Some of the existing drawbacks of current infrastructure of health systems in Finland, Europe and around the world are reviewed, specifically from the viewpoint of Health Care Facilities (HCF), and a novel approach is conceptualized which could potentially resolve some of these issues. The conceptual explorations for design solutions are facilitated by utilizing some of the well-recognized methods in engineering design for concept exploration and conceptual design. The approach in the engineering design has been systemic, meaning that certain sets of principles and methodologies that yield the design solution have been followed, making it understandable for any other designer to continue with the process of design and also reassuring that the design decisions are thoughtfully made, and that these decisions are not subjective.

Applications of the Engineering Design Methodologies and Extension of Methodologies

Existing methodologies of structural design, product design and in a broader term, engineering design, have been applied and I have also developed new methodologies in the design thinking to facilitate the decision making in the design process.

A New Approach for the Design of Health Care Facilities with a Modular System

Looking at the different levels of healthcare facilities as a whole, a potentially disruptive concept has been introduced that if implemented with care and effort can create dramatic changes in the current infrastructure of healthcare facilities. The concept is modular, allowing for standardization in the manufacturing process and customization of the design to be used for various purposes. The concept is made up of multiple units that will be distantly situated and they need to be remotely connected to the main controlling system via a digital infrastructure. Modular units can be manufactured using direct digital manufacturing technologies with great precision and they can be assembled in a fast and efficient manner. The solution has multiple use cases in different environments of health care facilities. Moreover, it can have multiple other use cases in contexts other than health care since it is customizable and adjustable for other needs and requirements. Nonetheless, in this thesis the focus will be on the context of health care since the requirements for a health care unit are quite complex and need a great deal of research to be conducted. The results of the design can be then simplified for many other simpler use cases of the product. The most urgent needs for this product in the health care facilities have been identified and a number of necessary requirements for the design have been gathered. Requirements for different use cases are very diverse, and thus, the course of the initial conceptual design was started by narrowing down the use cases while trying to find the similarities in the requirements of different cases and lowering the amount of diversity in the final design solution.

Significance of the Research Problem

Here, some use cases of the proposed solution in the context of healthcare facilities will be briefly presented. In the following chapters it will be described how it can serve to alleviate some of the problems with the existing solutions. The importance of the problems that are being solved will be discussed and some immediate markets for the product will be introduced.

By looking at the existing literature in the development of health care systems and facilities it has been found that nowadays some critical problems exist in the medical environments. There are several research studies that conclusively prove the superiority of single-bed room hospitals over multi-bed room hospitals, and the multiple reasons for this will be covered briefly in the literature review section.

One of the use cases of these units that are called “SPACYPHY” units in health care environment is that these units can be used as single patient rooms to serve patients in hospitals. The name comes after the fact these units will create a physical space for a specific use which has cyber infrastructure. SPACYPHY units can be installed inside the hospital building (in the dorms, in corridors, or any other unused space) to serve as a fully functional single room for one patient.

Another area where there is enough literature to support the need for innovative solutions for current and upcoming healthcare problems is the aging-in-place phenomenon. Finland has a relatively old population and an ever-growing number of elderly people that prefer to be taken care of in their own places and some need special treatment. Subsequently, in the literature review section an overview of the existing problems with aging in place will be presented.

Another use case for the SPACYPHY units is that they can be installed inside a residential building or house for the patients that need long duration medications. In the cases that adequate space inside buildings or hospitals is not available SPACYPHY units can be located outside of buildings and they can operate as an independent structure. It will be discussed how the designed product can facilitate the living conditions of the elderly.

While multiple other use cases for SPACYPHY units in the area of health care are found, the focus will be on the three use cases mentioned above (In hospital dorms, in homes, and as an external unit) for the detailed analysis and conceptual design in this thesis.

The product designed in this thesis can help reduce hospital acquired infections, can increase patient's satisfaction, and can shorten recovery times for patients. The approach is resource effective and saves energy and costs. Hospital at home programs and remote patient monitoring systems can be integrated into this developed concept.

Goals and Objectives of the Thesis

Some of the basic goals and objectives that were set prior to this research to be aimed towards are presented here. The reasons to follow these objectives and the motivations for investigating them will be discussed with further details in the next sections of this thesis.

Modular Unit Design Suitable for Mass Production and Distribution

One of the goals in this research is to promote the usage of modularity in the design of structures in the built environment. The design will be in a modular way for a variety of reasons that are covered in the background section of this thesis.

Product Development Techniques to Be Used in Structural Design

Many principles that have emerged in the design of products other than buildings have been applied, and in this research some of them will be used to judge whether they are applicable and useful methodologies or not for the design of buildings and infra projects.

Developing a New Concept as a Solution for the Problems Related to Healthcare Facilities

The results of the reviews and developments in this research are applied in the design of a new concept that will help improve the quality of healthcare in the society. Nevertheless, the detailed design of the concept was beyond the scope of this thesis and requires further research and work.

Exploring the Use of Collapsible Mechanisms to Save Space and Energy Consumption

One of the primary focuses in this conceptual design project, was lowering the energy consumption, increasing resource effectiveness and saving of useful space. Mechanisms that allow the mode change of the space from active to idle by reducing the size of the space are sought. This design tries to create a solution which is compactable to at least half the size when compacted. The result of this design can be used for a variety of other purposes that will be briefly outlined later.

Exploring the Concept of a New Ecosystem of Connected Distant Facilities

One of the goals of this thesis was to explore a revolutionary, platform-based concept that can create a network of building units that are all connected together, are distributed, such that many users and owners can access and use them. While the healthcare business has been looked at in this thesis as a specific use-case, the results of this research can be applied to many other business areas.

Exploring the Potential Consequences of Using Direct Digital Manufacturing Technologies on Structural Design

One of the other objectives of this research was to explore the effects of utilizing the DDM technologies as the main manufacturing method in this project. The aspect that is particularly interesting to look at is the limitations of current technologies and the changes that upcoming technologies in this area in the future can impose on the design phase. In other words, the new opportunities and limitations that are being raised for the designers of products and structures have been examined.

Increasing the Resource Effectiveness through the Use of Engineering Design Methodologies

In this thesis, current methodologies to improve resource effectiveness in the design have been explored and new methodologies for this purpose have been introduced and utilized in the course of the conceptual design. Developing methodologies to support, resource effectiveness of the design solutions in conceptual design stage will remain one of the main goals of this thesis. To apply all the techniques and methodologies and to expand the current methodologies to fit my purposes and improve them further, the conceptual design of a modular healthcare unit has been used as a case study.

Research Methodology

The methodology of the research in this M.Sc. thesis and the chronological order of different investigated areas are illustrated in the flowchart below (Figure 1):

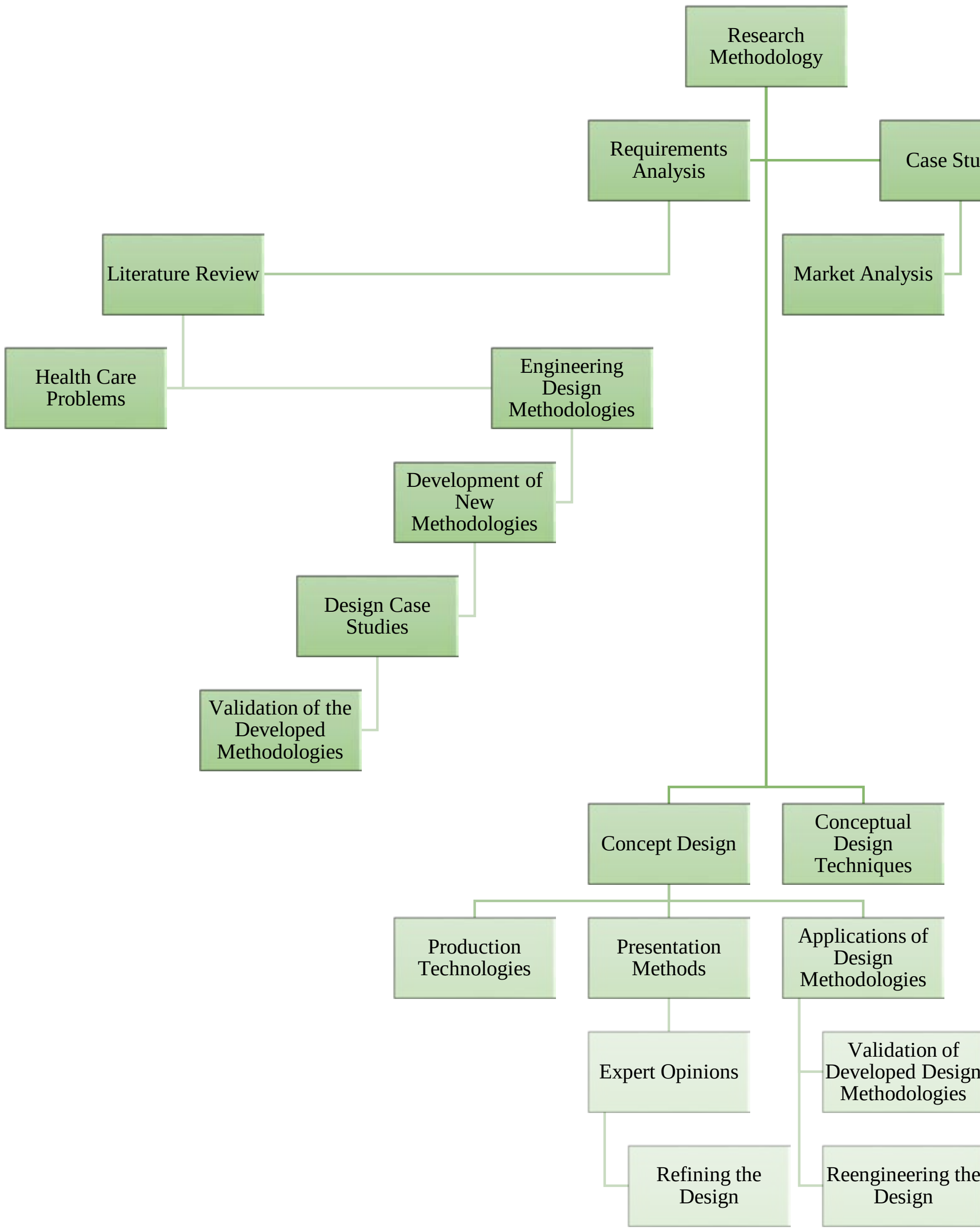


Figure 1. Research Methodology

In the early stages of conceptual design, I began to gather as much of customer requirements that I could. I did the market size analysis and chose the target markets. Thereafter, I did research on what are the exact needs of each type of users and searched for their requirements. To do so, design guide books for healthcare facilities in some states in the US and in some other countries were searched and in this way some basic sets of functional requirements of the units could be derived. Later, the relevant literature on the problems in hospitals were investigated and the research journals in that area were read to identify the current prevailing issues. Another source of information for gathering customer requirements was results of patient satisfaction surveys published online that one could sense and collect the demands of patients in them. Collecting customer requirements requires a good knowledge of who are the customers and how they will be interacting with the design. It was a very time-consuming part of the project and it evolved through the course of the design as more and more requirements were discovered when design decisions had begun to be made. Later in the next chapter the method used to organize and validate these requirements will be described and some of the most important criteria that was accounted for in this design will be discussed.

After discerning what the problems that I was trying to solve were, I searched for similar projects and solutions globally to see the innovative solutions that already exist and whether it might be possible to utilize them in this design. Through this review of the typical existing solutions it was possible to compare their advantages and disadvantages. I also tried to think about any other alternative solution that can turn out to be more effective than this and then I was able to compare the design with all those alternatives to develop it further. The methodology that was used for this comparison between alternative solutions and alternative design approaches will be explained in the following chapters.

While I was designing different alternatives I realized that the existing engineering design methodologies do not necessarily address some important aspects of the design that I was facing in this project and their consequences. Thus, it required that I attempt to develop these methodologies further. In this thesis, it has been sought to promote computational design thinking and systemic design rather than conventional design methods where the designer often makes all the design decision without necessarily being explicitly aware of the process of decision making itself, which often leads to subjective biases and mistakes in the decisions. The domain of ‘Product Design and Development’ has a good background in well-established methodologies for the design and it has been one of my objectives to integrate those techniques in the structural design projects by examining the presented project as a design case. Therefore, this project was analyzed using the newly developed methodology during this project to validate the methodology itself and to improve the design at the same time. Since the introduced methodology requires the gathering of customer and expert feedbacks, it was an important step to present the design with different methods and forms. So, after that the initial version of the concept was made, 3D models and visualizations were made, prototypes were 3D printed, and simulations were made using animations and virtual reality technology. After presenting the initial concept to experts, users, and gathering their feedbacks the design can be developed further.

It is hoped that the methodology of this design can be thought of as a new approach in making more aware design decisions in civil and structural engineering. After all, one of the important goals of this thesis was also developing a prototype solution to serve for introducing an innovative way of modular design of distributed healthcare facilities.

Theoretical Framework

Product Design Approach in Structural Design: Establishing Connections

Product designers have used a variety of tools in their design processes and approaches, and many of those tools are proven to have significant impact on the quality of their final products, cutting the costs and reducing the manufacturing and delivery time (for instance QFD Analysis, Structure Sharing Methodologies, Axiomatic Design Techniques, Design Prototypes, Set Based Design, etc.). In this research, while looking at the design in a broad view, and assuming adequate similarities in the approaches of human designer in different fields of science and technology and art, it was possible to take into use the different toolsets that have been developed over time to help design decision making for the purposes of this thesis. There are numerous tools and approaches developed by product designers that can be also applied in the design of built environments and other large scale artefacts. In the limited time of this master's thesis, I could look into some important tools and techniques like making a product storyboard, customer requirements analysis, QFD, prototyping, CAD tools, and computer simulations. Nevertheless, this theoretical framework, must be tested further by looking into more tools and processes in product design and also in other fields like game design, fashion design, graphics design, etc. to establish greater connections and to better understand how the design decision making can be facilitated, and how certain design tasks can be automated.

Exploring Potential Applications of Parametric Design and Generative Design in Structural Engineering

One of the possibilities in the designs of geometrical objects is introduction of parameters in an approach known as parametric design. BIM environment nowadays has enabled engineers to design parametric components and building blocks and it makes it easier for them to change their design in later phases. Also, the links that can be created between these parameters can lead to automatic updates of multiples forms of data management and visualization. This is already being widely used by civil engineers and it is being developed further day by day. Another area that should take considerable attention is the possibilities of introducing generative design techniques in civil engineering. As discussed earlier, it allows bringing automation in the design and it allows creation of a wide variety of design instances in a short period of time that can help in choosing the best alternative. As long as parameters can be defined to control the geometries and processes and as long as the logic of the design procedure is structured and perceivable, it is feasible to define those parameters and logic in a computer software and automate design tasks. In this thesis, the structure of the design procedure has been studied to find algorithms that are possible to be defined for a computer. It has been tried to understand the different steps of the design and it is hoped that this research yields to some further research in the design of a computational approach that can automate certain parts of the design decision making and in this way design mistakes can be reduced or eliminated, while increasing the performance of the designed solution in terms of quality and resource efficiency: time, cost and human labor.

CHAPTER 2: Background

Literature Review

This chapter will provide a brief overview on the existing literature relevant to this research in different perspectives. These overviews will form a better understanding of basics for the reader to be able to follow the works on the later chapters.

Problem Context: Single Bed vs. Multi-Bed Hospitals

As a result of physical proximity patients, guests, and hospital staff can transmit infections in hospitals. Thus, private rooms lower the possibility of infection transmission since there will be less contact between patients. Research showed that the nosocomial infection rate dropped by 50 percent in a pediatric intensive care unit when they changed from open ward to single patient rooms. Private rooms have proven to be beneficial for hospitals because of a number of different reasons namely reducing patient transfer, increasing occupancy rate, reducing the duration of stay, declining the risk of medical errors, reducing patient falls, lowering infection rates and improving overall satisfaction of patients. Private single rooms usually have sinks to wash hands regularly, and so, it reduces the risk of infection transmission. Also, they are reducing the risk of indirect transmission of infection from patient to patient (Van Enk, 2004).

In Figure 2, a comparison between the infection rates of new hospitals vs. old hospitals is depicted. Newer hospitals have higher proportions of single bed rooms.

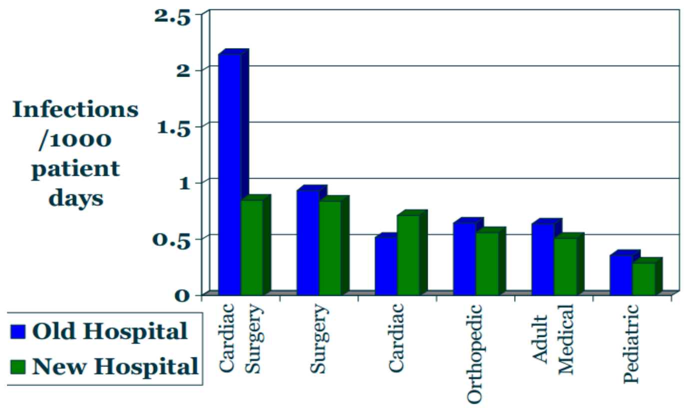


Figure 2. Infection Rates by Patient Care Unit (Van Enk, 2004)

In Figure 3, infection rates are categorized with the type of infection to see which infection types are reduced more in the newer hospital systems:

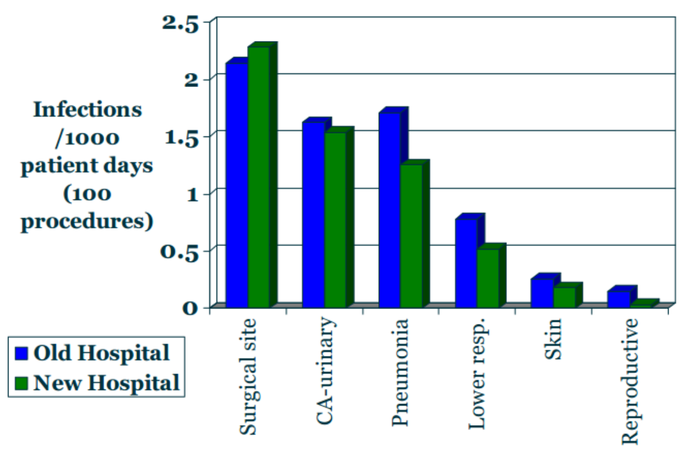


Figure 3. Infection Rates by Type of Infection (Van Enk, 2004)

Some of the noteworthy key points found in the relevant research projects are listed below:

- Here it is worth noting that one of the biggest motivations for finding a better solution was that design of the private room requires more space for each patient and it is more expensive to build.
- The costs that are saved by reducing infection rates and operational time can make up for the capital costs in the beginning.
- Patient satisfaction surveys prove as well that patients and hospital staff prefer private rooms.

- Healthcare associated infections (HCAI) can increase the costs of hospital for 40,000 $ per patient in US (Ulrich and Zimring, 2004).
- Single-bed rooms are easier to decontaminate after the discharge of the patient.
- According to studies moving the patients from open wards to private rooms can decrease up to 50% in infections (Ben Abraham, Keller, Szold et al., 2002).

Figure 4 demonstrates how infection rates were decreased substantially after the new design of hospitals was introduced in Jan, 2001:

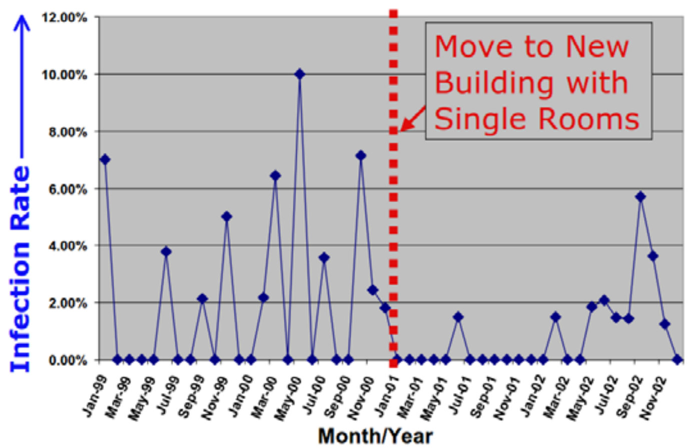


Figure 4. Infection Rates for Cardic Surgery Unit (Van Enk and Nyirenda, 2003)

Results of research shows that 85 to 90 percent of the times the hospital roommates are not providing positive social support but they are a source of stress by being unfriendly or seriously ill or by making much noise (Gesell and Malone, 2002).

Results of research based on data from 152,399 female patients in 566 hospitals across 46 states in US shows how the surrounding environment can affect satisfaction of patients. Figure 5 shows some environmental criteria in comparisons between shared rooms and single rooms:

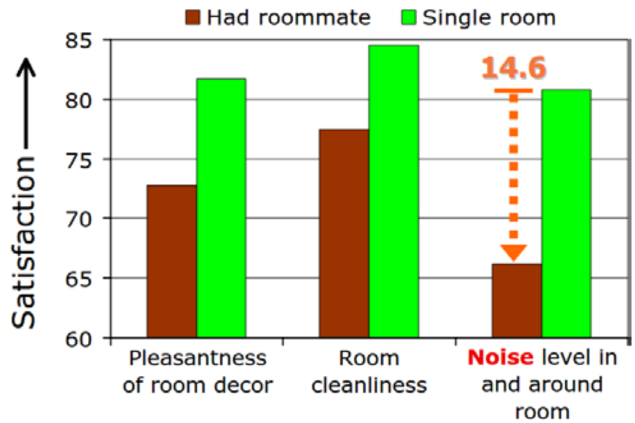


Figure 5. Satisfaction with Room Environment Aspects (Gesell and Malone, 2002)

Transfer of patients, caused frequently by incompatibility between patients, leads to infection growth while increasing medical errors and staff time (Hendrich, 2004).

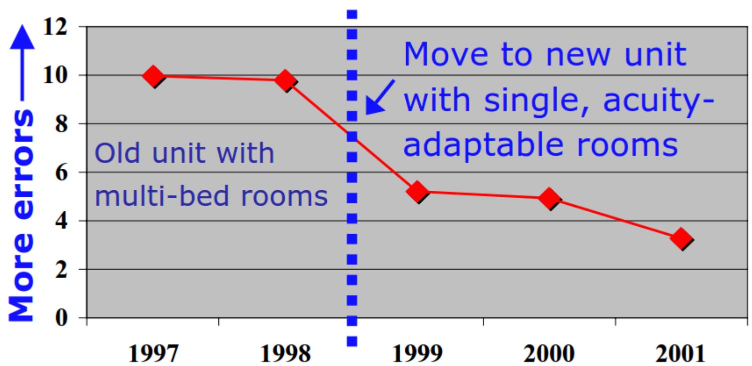


Figure 6. Annual Medication Error Index (Errors/Patient Days) Coronary Critical Care (Hendrich, 2004)

Single-bed rooms can be designed to support the presence of family and this will assist the patients when getting out of bed and prevents falls. Research shows that caring family and friends can reduce stresses and enhance medical outcomes (Hendrich, 2004).

Visual observation of patients is improved, resulting in increasing safety. Decentralized nurse stations, acuity-adaptable and family-centered care models all help to reduce the number of nurses required to be hired (Hendrich, Fay and Sorrells, 2004).

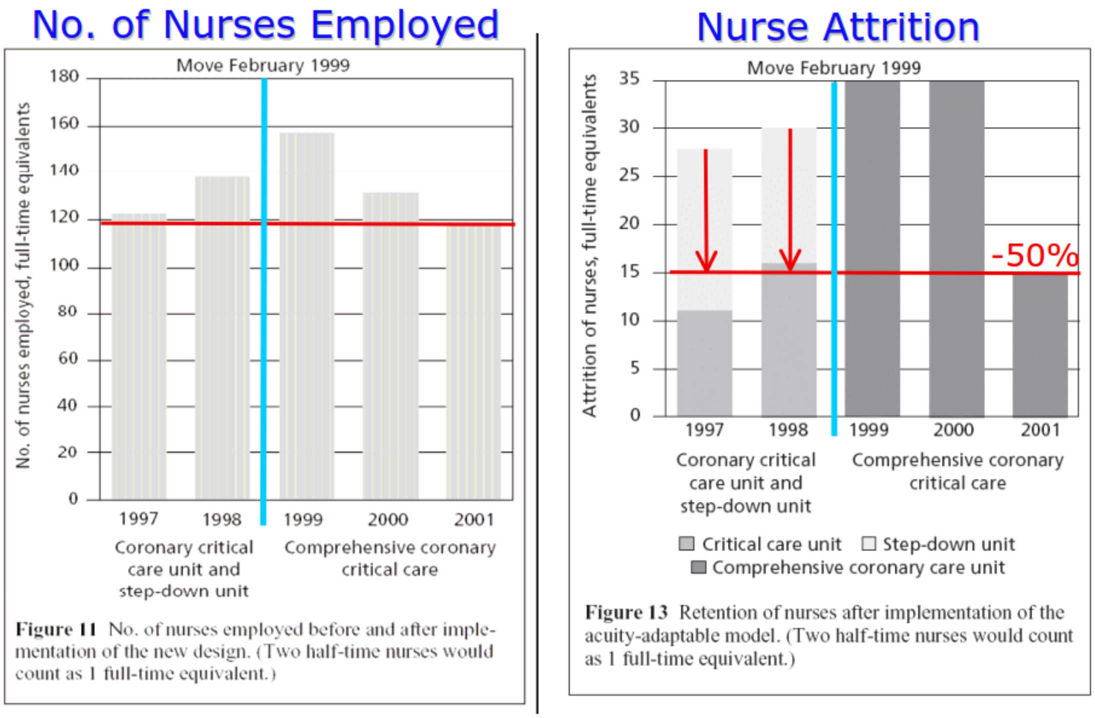


Figure 11 No. of nurses employed before and after implementation of the new design. (Two half-time nurses would count as 1 full-time equivalent.)

Figure 13 Retention of nurses after implementation of the acuity-adaptable model. (Two half-time nurses would count as 1 full-time equivalent.)

Figure 7. Staffing Impact (Hendrich, Fay and Sorrells, 2004)

One of the most significant sources of stress is the poor staff communications with patients. Decentralized nurse stations can increase patient's physical transparency leading to improved safety.

According to a study over 4.5 million patients in US, patients are more satisfied when they receive care in single rooms (Press Ganey US national data, 2002). Similarly, in UK, a high proportion of patients are more satisfied with single-bed rooms (Lawson and Phiri, 2003).

Ulrich (2004) presents the table shown in Figure 8 to illustrate all the benefits of single care rooms over multi-bed care rooms:

	Single	Multi-bed
HCAI	✔	
Medical errors	✔	
Falls	✔	
Staff observation of patients	✔	
Staff/patient communication	✔	
Patient confidentiality, privacy	✔	
Presence of family	✔	
Death with dignity	✔	
Noise	✔	
Sleep quality	✔	
Patient satisfaction	✔	
Patient stress, pain	✔	
Room transfers: costs	✔	
Managing bed availability	✔	
Adaptability to accommodate change	✔	
Initial construction costs		✔
Whole life costs	✔	

Figure 8. Single-bed vs. Multi-bed Rooms (Ulrich, 2004)

A New Trend: Remote Patient Monitoring

The outcomes of all of the new technologies that have evolved in the area of remote patient monitoring will be integrated in the concept. It reduces costs of healthcare, prevents overcrowding of emergency rooms, can help in monitoring elderly patients, and reduces medical errors and infection rates. There are hundreds of new devices and technologies evolving nowadays to allow real-time face-to-face communication between patients, doctors and staff, transmission of data from patient to the physician's EMR system, controlling blood pressure, glucose and other vital signals remotely, and automatic update of the status and records of the patient. However, economical issues are one of the hindering problems in the way of these devices. Also, it is crucial to pay attention to compatibility of all of these devices with each other and this is something that is considered in the designed concept. Currently these devices are standalone, and so is the healthcare facility. The proposed concept envisions a scenario where the devices and the healthcare units can communicate with each other and with the central system, creating an integrated ecosystem that improves access to quality healthcare. Moreover, privacy issues can be resolved in the concept by connecting the units to a central system that controls the accessibility of the different users to different pieces of information through authentication and access management (Lewis, 2012).

Problem Context: Aging in Place

While in Finland and Europe the growing population of elderly is giving an alarm on the upcoming challenges and needs in providing health care for them, in less developed countries according to a WHO article the ageing population is changing the nature of requirements in health care systems and other issues such as child care and maternal care as well are attention grabbing (WHO, 2007). Traditional methods of geriatric care are dependent on sophisticated facilities and homes to serve this purpose. However, innovative solutions utilizing the digitalization technologies and monitoring technologies can create newer approaches to reinforce the current infrastructure and homes and hospitals for the geriatric challenges. The focus in the approaches in providing health services can be on the prevailing issues that relate with many senior citizens such as falls, dementia, mobility, injuries, etc.

This thesis aims to develop and pilot a new product and service system that brings a new approach in dealing with geriatric or pre-geriatric care so that it suits the postural changes and reassures the mental health of the elderly. Many areas of science and technology will assist in the design of this innovative solution namely, Internet of Things (IOT), Virtual Design and Construction (VDC) and technologies such as Building Information Modelling (BIM) and Product Lifecycle Management (PLM). Preventative and responsive care is supported through the development of smart spaces, remote monitoring systems, communication systems, assistive devices, tracking systems, measurement devices, etc. and errors in the design and medical errors will be reduced.

The concept allows digital linkage between physical spaces for better monitoring and tracking and better quality of services and better social interactions. Real time monitoring and feedback reduces the risk of medical errors. The concept must well adapt to the existing socio-physical environments and it has to be robust enough not to deteriorate in time. I hope that the conceptual design done in this thesis leads to pilot tests and prototypes under the supervision of healthcare authorities to achieve all the intended goals and to be developed further. Posture monitoring systems have been thought of to be implemented in the solution. And, that requires enough hardware and software infrastructure to be developed generating new product design problems, IOT communication network, data collection and analytics. Postural changes and the way senior people interact with their physical environment imposes new challenges in the product design and software design part. Extra facilities need to be provided to assist them in their daily life activities such as getting on and off their bed, getting in and out of toilet, moving around, sitting and standing, entry through doors, etc. to prevent the risk of falling and also extra monitoring and feedback systems need to be provided that require a well-established software infrastructure to be developed. Through the development of software and apps smart notification systems can be used to help in reducing stressful situations for the elderly and their family members.

The concept will allow the elderly people to age in their own surroundings and provides safety for them and at the same time gives the highest degree of privacy and independence and a customizable design platform can create a wide variety of options and functionalities for the end users. One of the most important values in the eyes of elderly people is that they demand to make their own decisions. They want to be in full control of their lifestyle and want to have autonomy and don't want to be dependent on anybody else (Olsberg, 2005). They have a sense of attachment to the place they have lived for long since it guarantees them with a feeling of security and privacy. The idea of Aging-in-Place centers on continuing to live in the society, but not necessarily a full-sized home. In fact, any type of accommodation that enables the elderly to stay in their surroundings where they belong can be classified in this category. Other important values for the elderly, are the design of their neighborhood, the ease of access to other parts of city by public transport, comfortable and convenient walk-ways and connections, easy ways of communication, their ability for receiving more education, and health monitoring systems to continuously check the vital signals and reassuring about their well-being.

Research has revealed what can be the best place to grow old in the perspective of the elderly people. Having multiple options, sense of belonging to the place, security and being familiar with the place are the key factors in their view. It should provide the accessibility to family and friends while maintaining the independence and autonomy of the elderly (Callahan, 1993; Keeling, 1999; Lawler, 2001). Taking care of old people in their own home cuts unnecessary costs of hospital care and has proven to be more satisfactory in the view of elderly as well (World Health Organization (WHO), 2007).

Removing physical obstacles and adding aids for moving can help create a better physical environment for old people (Lawton, 1982). The solution for the design of spaces for aging in place must provide ease of communication and access to family, relatives, and friends as they can help alleviate positive feelings of support. Research has investigated the costs and advantages of care at home over institutional care. Aging-in-place is a complex term in the sense that the older people must be able to adapt to their surround environment as the society, and their own home, which are continuously altering, and there has to be social and health services available to assist old people (Andrews, Cutchin, McCracken, Phillips, & Wiles, 2007).

Sense of belonging to a place can promote security and create meaning for older people (Rubinstein, 1990; Taylor, 2001). Neighbors and community are also important factors for the satisfaction of older people from their dwellings as they are more sensitive. As a matter of fact, urban planners and infrastructure designer do not necessarily consider the old people suitability or the design of age-friendly environments (Laws, 1993; WHO, 2007).

Results of interviews with old people showed that one important factor for them was freedom in choosing among solutions and accessibility to services and not feeling to be trapped in a place. Older people tend to have a strong sense of attachment to their local community and to their social communications. Some, consider the access to public transport very important and they have a special connection to their close neighbors. Some, have a close connection to the physical space as a result of living there for many years (loving their garden as an example) and they have made many good friends in the same area they live that they don't want to be detached from them. Most old people agree that they are no longer interested in maintaining very big spaces and spare rooms in big houses. They do not see any reason to move to another house or their children's house as long as they feel fit to take care of themselves and enjoy the social activities around them. Long as they feel comfortable and happy about their place they don't want to move even to a family member's house and being attached to one place might even hinder the person's opportunity to move to a more appropriate place when it is important to do so. Each home has its history and by living in it for a long time older people feel more secure as they know where things are, they have contacts nearby to help them in emergency and familiarity creates security for them. In the course of life people shape their surroundings with the styles that is favorite to them and they don't want to repeat the things they have done for a new place that doesn't seem right to them (gardening, coloring, decorating, buying stuff, etc.).

Older people give a significant value to the familiarity with their local community and their friends in the neighborhood that can look out for them and come for help in case of emergencies. It is quite difficult for older people to adjust themselves to a new place and the new community there while they have enough information about their local shops, supermarkets, facilities, activities, and so on.

Another important aspect of aging in place for older people is that they would like to feel independent and able to do things and thus, prefer staying in their own home to hospital care. They want to have full control of their lives and decide on every small thing in life. Many elderly people regard the current solutions for elderly care centers very restrictive and limiting for their decisions and also find the additional support and security provided by them quite costly and unaffordable. Interviewees of the research expressed sense of identity to their old local neighborhood and found it difficult to move and get to know all the new people and places and they emphasized on the fact that they most of all want to be in charge of all their decisions and don't want anybody else decide about where they should live for them (Wiles et al., 2011).

The concept takes into account all these values as the design requirements, since the increasing population of elderly people places them to be one of the significant customers.

A New Trend: Hospital at Home Programs

Some doctors prefer visiting patients at their own place to get some sense of the context for their medical issues and while giving importance to the patient's preferences for care plan development.

Some patients with pneumonia, exacerbations of chronic illness, heart attack or stroke might refuse to go to hospital. In hospitals schedules are imposed to patients that might not fit their preference, the food served is not of the best quality and sleeping is harder for the patient.

20 years ago, John Hopkins asked, "Could acute medical illness that normally requires hospital admission be well managed in a patient's home instead?" and the answer was development of HaH (Hospital at Home) specifically for the patients with pneumonia, exacerbations of heart failure, chronic obstructive pulmonary illness, cellulitis, etc.

The patient in the first place is checked by the physician in the emergency department to confirm that he/she is sick enough and is meeting the clinical-appropriateness criteria for HaH. However, patients with uncorrectable hypoxemia (low blood concentration of oxygen) and ischemic chest pain (resulting from insufficient blood supply into the heart) are not appropriate for the HaH (Leff, 2015).

HaH services like oxygen, respiratory, infusion therapy, nursing staff, etc. can be supplied from the hospital, health-system sponsor, or partner vendors.

Patient is taken home by ambulance with oxygen and a HaH nurse educates the patient and the family at home and makes sure that all services are active and then reports the status of the patient to the HaH physician so that an appropriate care plan can be selected for the patient. The HaH care team are available 24/7 for emergencies and skilled therapists are sent if needed. The nurse and the physician visit the patient with a regular routine as well. In some cases, patient might need tests that can't be provided at home and so he/she is transported to the hospital for the test and then back home.

Results of the researches show that hospital at home causes fewer difficulties like drastic reduce in delirium and patient and their family are more satisfied, care team faces lower stress, functionality improves and costs are reduced.

Payment mechanisms, timing in the delivery of the services, and admission of patients in any point of day or night, and the patient's first impression when HaH is offered in the emergency unit can be challenges for implementing HaH.

HaH well suits early-discharge-programs, skilled-nursing-facility care after hospital discharge, and post-surgical care. Future technologies will serve to increase the profitability and performance of HaH naming biometrically enhanced telehealth modalities.

Reducing the need for building new hospitals and infrastructure replaced by HaH admissions of patients can result in a drastic return for the investment making it easy for scaling up the HaH service (Leff, 2015).

In the presented vision, an adjustable unit that can be installed in the patient's home and can be integrated into HaH programs is being designed. While patient is relocated from hospital to home by ambulance, the expandable unit modules can be transported and assembled in the apartment in a very quick manner and patient will be kept there under sufficient control of hospital staff.

Physical Features of the Built Environment That Can Have Influences on Health

One of the key steps in the design of health care facilities is identifying the important features of the interior space that directly affects well-being of residents. Looking into the existing literature indicates that acoustics, air quality and ventilation, lighting and visual aesthetics, ergonomics and furniture have beneficial effects for patients when designed with care. Nevertheless, other factors such as room layout and floor finishes may have advantages and disadvantages for specific user groups. Apart from the direct impact of physical items on health, they might as well impose indirect effects on the users depending on their interactions with the space and the behaviors of different physical objects (Salonen et al., 2013).

Nightingale (1860) attests that in the presence of natural light and sufficient ventilation and sanitation, patients will recover faster. However, current health care facilities may be thought of being stressful and institutional and they may not necessarily physiologically support the needs of patients (Ulrich, 2000; Stichler, 2001; Ulrich et al., 2004, 2008; Dijkstra, Pieterse, and Pruyn, 2006; Ampt, Harris, and Maxwell, 2008; Dijkstra, Pieterse, and Pruyn, 2008).

The main approach in the design of health care facilities has long been evidence-based design (EBD) which relies on redesign and adapting the design based on research (Goetz et al., 2010; Carr, 2012). Research based design which has been the chosen approach in the design of the SPACYPHY units can reduce medical errors and infections, can improve sleep quality and privacy and can reduce levels of stress and pain in patients and can boost the performance levels of staff (Lundstrom et al., 2002; Tanja-Dijkstra and Pieterse, 2010).

According to scientific evidence, decentralized nursing system can reduce the walking time of nurses and thus helps achieve faster care. Nonetheless, it might hinder the ease of communication between nurses

(Tyson, Lambert and Beattie, 2002). In the concept, the latest communication technologies available such as mobile apps and remote controlling devices will be handed to staff members to encourage team connection and collaboration between colleagues. Research recommends the allocation of a family zone inside single patient rooms or in a separate room where family or visitors can sleep over night since it enhances social interactions and family support and reduces the risk of patient falls (Douglas and Douglas, 2004; Johnson and Abraham, 2004; Joseph 2006; Kutash and Northrop, 2007; Carr, 2011). However, susceptible patients to infection and infectious patients and psychiatric patients who need to be monitored should not stay in the family areas (Tyson, Lambert, and Beattie, 2002).

Floor coverings can be important in reducing nosocomial infections since larger amounts of infection can accumulate on porous materials like carpets. Hard floor coverings are easier to clean and dust does not easily get back into air by physical activities from smooth surfaces (Gravesen et al., 1986; Thatcher and Layton, 1995; Leese et al., 1997; Qian and Ferro, 2007; Harris, 2000). Thus, hard and glossy materials such as vinyl and linoleum are suitable for floor coverings (Ulrich, 2000). On the contrary, some other research proves that carpet is easier to clean (Lankford et al., 2006) and some pathogens survive longer on harder surfaces and carpets transfer less pathogens in comparison to vinyl and rubber flooring (Lankford et al., 2006). Carpets reduce noise levels (Willmott, 1986; Counsell et al., 2000; Harris, 2000; Joseph, 2006) and glares (Carpman and Grant, 1993; Horton, 1997; Harris, 2000), provide ease of walking and reduce risk of falls and injuries (Willmott, 1986; Counsell et al., 2000; Harris, 2000; Joseph, 2006) and create a more relaxing and home like atmosphere (Cheek, Maxwell, and Weisman, 1971; Glod et al., 1994). On the other hand, carpets make it difficult to push wheelchairs, carts and gurneys (Harris, 2000) and fungi and bacteria can grow faster on carpets (Anderson et al., 1982; Skoutelis et al., 1994; Beyer and Belsito, 2000; Joseph, 2006). All in all, the use of carpets in areas where spills are probable and when patients are at risk of airborne infections must be avoided (Sehulster et al., 2004).

One of the main reasons for patient’s complaint is noise (Ulrich et al., 2008). Using sound absorbers and high level of sound insulation can improve the quality of sleep and overall satisfaction of patients and accelerates their recovery. Enough sound insulation provides privacy and confidentiality for patients and reduces noise levels inside the units which results in reduction of pain and stress and headaches and exhaustion and also decreases blood pressure and heart rate and consequently shortens the length of stay in the hospital (Hilton, 1985; Evans and Cohen, 1987; Yinnon et al., 1992; Grumet, 1993; Biley, 1994; Bayo, Garcia, and Garcia 1995; Slevin et al., 2000; Johnson, 2001; Hagerman et al., 2005; Johns Hopkins University, 2005; Chaundhury, Mahmood, and Valente, 2006; Mazer, 2006; Beyea, 2007; Joseph, 2007; Joseph and Ulrich, 2007; Ulrich et al., 2008). Moreover, noise reduction can help the staff members with reducing stress and work pressure, fatigue and medical errors (Flynn et al., 1999; Zun and Downey, 2005; Joseph and Ulrich, 2007).

Indoor air quality must be maintained through the use of proper ventilation and air conditioning systems. It directly affects the occurrence of respiratory disease, allergies, chemical sensitivity and asthma (Fisk, 2001; Joseph, 2007). It also affects the rate of airborne infection transmission and performance of staff. In the case of patients at risk of airborne disease, it is fundamental to provide negative air pressure. In addition, guidelines suggest a minimum rate of outdoor ventilation for infection control (Tang et al., 2006; CDC and HICPAC, 2007; Li et al., 2007; Eames et al., 2009; Tunga et al., 2009; Zhao et al., 2009; Balocco and Lio, 2010). In case of high risk patients, Aspergillus infection for instance, High-Efficiency Particular Air (HEPA) filters have proven to be effective for reducing the infection rates of many aerosolized pathogens (Withington et al., 1998; Hahn et al., 2002; McCann et al., 2004; Eckmanns, Ruden, and Gastmeier, 2006). Natural ventilation may not be very effective since it does not provide negative air pressure, and outdoor climate is not very stable (WHO, 2009).

Thermal conditions have a considerable effect on physical comfort in health care facilities (Hwang et al., 2007; Wu, 2011). It also influences the duration and quality of sleep and recovery of patients. Research shows that too warm temperature can reduce sleep time (Parmeggiani, 1987; Okamoto-Mizuno, Tsuzuki, and Mizuno, 2004) while too cold temperature brings in the difficulty of getting to sleep and staying sleep (Okamoto-Mizuno, Tsuzuki, and Mizuno, 2005). Additionally, thermal environment has proven to be effective in performance of staff members and their productivity (Mackworth, 1950, Ramsey and Kwon, 1988; Kaplow and Hardin, 2007). In general, physical discomfort can promote irritability and errors for staff. However, the definition of a pleasant temperature is very subject dependent and varies person to person. Research demonstrates that people with less physical activity can tolerate higher temperatures (Wu, 2011).

Lighting provided in the health care facilities needs to be enough and changeable. Natural daylight is preferable, but artificial lighting is as important (Devlin and Arneill, 2003). Daylight effect melatonin production and enhances circadian rhythms, and influences vitamin D metabolism, reduces pain and stress and improves quality of sleep (Walch et al., 2005; Dijkstra, Pieterse, and Pruyn, 2006; Joseph, 2006; Ampt, Harris, and Maxwell, 2008; Ulrich et al., 2008). It changes mood and prevents depression and generally shortens recovery time (Edwards and Torcellini, 2002; Ulrich et al. 2004, 2008; Dijkstra, Pieterse, and Pruyn, 2006; Joseph, 2006; Lorenz, 2007). Daylight can also reduce stress levels of staff and increase their performance and help them achieve a good mood and job satisfaction (Robbins, 1986; Edwards and Torcellini, 2002). Bright artificial light can help reduce depression. Bright light increases alertness and work accuracy, and also aids the elderly and reduces falls. Patients must have full control over lighting to promote feeling of independence and reduce stress (Dijkstra, Pieterse, and Pruyn, 2006; Joseph, 2006; Lorenz, 2007; Ulrich et al., 2008).

According to studies, having view and access to nature through a window can reduce stress, anxiety, delirium, depression, blood pressure, heart rate, sleep disturbance and hallucination (Wilson, 1972; Parker and Hodge, 1976; Keep, James, and Inman, 1980; Ulrich and Gilpin, 2003; Ulrich et al., 2008; Ampt, Harris, and Maxwell, 2008). A view to nature can create a sense of being normal for patients and helps them recover faster and improves their satisfaction (Kaplan, 1992; Clay, 2001; Ulrich et al., 2008). A window opening to nature also reduces the work pressure and stress for staff and increases their productivity. It prevents headaches and distractions and improves concentration (van den Berg, Hartig, and Staats, 2007).

Research shows that using outdoor living things like plants and flowers inside health care facilities can reduce stress and pain of patients while it improves aesthetics of the rooms (Dijkstra, Pieterse, and Pruyn, 2008). Guidelines recommend the use of plants inside health care facilities in most cases except in the case of rooms with immunosuppressed patients (CDC and HICPAC, 2003).

There has been a link between the use of certain colors and creation of certain moods. Warm colors tend to energize and activate while cooler colors tend to be more calm and relaxing. However, the physiological findings are not very reliable because of their limited color samples and sample groups. And, the correlation between colors and emotions have not been scientifically validated yet. Response of individuals to different colors is the stimulus for their emotions and this response can be different from person to person (Fehrman and Fehrman, 2004; Tofle et al., 2004).

Works of art creates a friendly atmosphere and changes the institutionalized sense of the health care environments. It suits the emotional well-being of patients and increases their satisfaction. Studies shows that realistic arts which illustrates nature can reduce stress and anxiety levels. The use of abstract art and complex art might increase levels of stress and it is often not preferred by patients (Ulrich, 1991, 1992, 1999). Nonetheless, more studies are needed to measure the effects of artworks on patients and staff.

Ergonomic design must be utilized in the design of health care facilities since it prevents injuries and it provides the most optimized solutions that support physical comfort. Ergonomics is a science that studies the way people interact with the physical objects and tools around them and it aims to increase performance and comfort and prevents long term physical illnesses (Springer, 2007). It also focuses on the use of different mobile devices and communication tools that facilitate the work of staff members in the hospital (Walls, 2001; Amick et al., 2002, 2003; Nevala and Tamminen-Peter, 2004; Springer, 2007). Furniture design is covered in Ergonomics as well and it can have reducing effects for nosocomial infections. Design with Ergonomics principles reduces the risk of patient falls and injuries and improves the quality and ease of communication between family and patient and between staff members (CDC and HICPAC, 2003; Lankford et al., 2006; Bartley, Olmsted, and Haas, 2010; Carling and Bartley, 2010; The Facility Guidelines Institute, 2010; Malone and Dellinger, 2011).

People have a wide preference when it comes to listening to music, but listening to the type that they like in health care facilities can improve their satisfaction and well-being. Research proves that pleasant and controllable music can lower stress, anxiety, blood pressure, heart rate, agitations, and increases the level of tolerance of patients in coping with problems and pain and thus shortens the recovery time (Standley, 1986; Menegazzi et al., 1991; Chlan, 2000; McCaffrey and Locsin, 2004; Chang and Chen, 2005; Cooke, Chaboyer, and Hiratos, 2005; Goodall and Etters, 2005; Lee et al., 2005; Lai et al., 2006; Joseph and Ulrich, 2007; Särkämö and Soto, 2012).

Design Engineering: How Do Engineers Conduct the Design?

The Process of Design: Design is claimed to be a mysterious activity by the designers in a way that it has not been recognized to be suitable for scientific experiments for centuries. However, recent research in artificial intelligence and its information processing models have considered design process to be an activity (Gero, 2006).

During this project, the design is considered as a process and it has been tried to engineer and improve the design process. This is not possible unless the designer himself can have a deep understanding of the design process and all the steps he is taking towards each of his design decisions.

Design can be defined as producing physical artifacts that suits the world around us for better conditions of life for humans. In a design activity requirements are transformed into artifacts that can obviate the expected need by performing a function and are demonstrated by the design descriptions in the forms of graphics, comments, and formulas to facilitate the manufacturing process. During the design process perception of the designer of the context of the design changes and so the context changes making the design process a learning activity (Gero, 2006).

Design in Engineering should be differentiated from the design in other fields, especially artistic fields like architecture, visual arts, etc. In industrial design, aesthetics, ergonomics and performance of a physical product is in the center of attention.

CAD (Computer aided drafting) has enabled us to transform the structure that can perform a function required by the customer into the design description. Functions are indirectly related to the structures by comparing the behaviors of the structures and the behaviors that are expected to form the functions.

By looking at design as a process and modelling it, these steps are needed to be taken: formulation, synthesis, analysis, evaluation, reformulation, and design description making.

Design can be categorized in the three classes of routine design, innovative design, and creative design (Gero, 2006).

A routine design is conducted in a well-known solution space that contains standard sets of answers for each problem. All of the requirements and needed information in this type of design can be derived from previous design works. The constraints that exist in routine design limits the choices of the designer to a great extent that the solution space is far smaller than the potential design space.

Innovative design also takes place in a well-known solution space but it differs from the routine design in that the designer might change the normal values allocated to different variables and the result is a new solution that has not existed before.

In the creative design, however, a new set of problems rises and new variables are created that can expand the space of the potential designs and it shifts the paradigm (Gero, 2006).

There’s a trend in introducing more and more computational processes in the design, mainly because they will assist human designers in their decision making and automation of different design tasks can be introduced. By bringing computational design and automation one can choose between many alternatives and more alternatives can be generated in shorter time that will lead to better solutions.

Generative Design: Generative design techniques have been developed to serve to automate different types and forms of design. In generative design, instead of engineering the final product the process of design is being engineered and then that process is automatic and the results are automatically generated. Thus, to be able to implement a successful generative design technique and to be able to build a platform where they can be applied to produce the solutions, it is initially needed to identify all that is happening in the human mind when they are doing a design activity. Design engineering is the area that can result in consistent true principles that exist in most of design processes (Ulrich, 1988).

Axiomatic Design: Another purpose of design engineering is to facilitate the learning process of design, because it is making it systematic and generalized and so easier to grasp (Pahl and Beitz, 1996). The axiomatic approach to design provides means to support decision making. It has a methodology to improve the quality of the design. The whole purpose of aiding design decision making is improving the quality of products, and making sure that it is buildable within a reasonable cost. Axioms are true principles that can’t be proven but there have not yet been found any counter example for them. There are axioms controlling the basis of each design and the important characteristics of the axioms are that they are general and are not case specific. The two fundamental axioms that have been discovered to exist in any good design process are independence axiom and information axiom. Independence axiom states that functional requirements that determine the quality of the solution must be kept independent from each other and information axiom states that the amount of information in hand should be minimized by picking up the design alternatives that have the highest possibility of success and neglecting the rest. Each of these axioms have multiple criteria and axiomatic design has methodologies. By discovering these fundamental axioms in the design process one can make the design process more systematic, which leads to reduction of cost and labor and time in the production and improving the quality of final products (Yang and Hongwei, 2000).

The presented case of this project can be thought of as a design problem that requires a design process that I was interested to study in detail to form a systematic approach for the similar design problems. In fact, it has been tried to avoid the conventional ad hoc and empirical design approaches in which the designer starts the design on a piece of paper or in a CAD software while he/she is not aware of the process in which he is selecting the proper dimensions, structures, behaviors, shapes, materials, etc. The target was to create a design framework that can be taught to future designers and the framework must always give consistent results with what is expected. In this way, we are moving towards quality, customer satisfaction, ease of manufacturing and building, automation and reduction of costs and human involvement.

Design Prototypes: What is the Significance of Design Prototypes in Conceptual Design?

During the exploration and learning process of the design the requirements are shaped as the design continues and the decision made will form additional features and unravel relevant information. Assemblage of concepts in different levels of abstraction can be schematized to depict function, structure, design description and behavior.

Design prototypes gather all the required information for a specific design activity together and creates a conceptual perspective for the inception and abidance of the design. Design prototypes are schematic, and they link the relations between function and behavior followed by selection of appropriate structures, and they tend to generalize the concepts and correlate the concepts to their similar archetype and they do not delineate the chronological sequence of events. Research on the design shows that designers correlate functions to the structures that they select and at very early stages of the design they pick some concepts and they will follow them. Design prototypes resemble all the knowledge that the designer is aware of when he/she is gathering requirements. These design prototypes focus the attention of the designer on certain items that he/she has to consider. Then the designer needs to select between these prototypes and prefer one to another. This selection of design prototypes lead to a design instance to be created as an alternative design. In a routine design, the designer is simply refining design prototypes. Using the available knowledge the designer is optimizing and resetting all the variables to remain within the acceptable range. In the innovative design, the designer needs to adapt the current design prototypes to the changes. In the creative design, design prototypes are adjusted and new prototypes are created. To create new prototypes the designer needs to change the context where he is working in (Gero, 2006).

Design prototypes can help to escape design fixation by representing the connections between structures and functions through behaviors. It can provide the means for the computational processes in all types of design (routine, innovative, and creative) (Gero, 2006).

Modularity: Necessary Steps to Create a Modular System? What are the Benefits?

Modularization has emerged through a mixture of customization and standardization, by looking at a module based on its structure or function. The main motives for modularization are lowering the level of complexity, increasing routine and repetition, while maintaining customizability (Martin and Ishii, 2002).

Customers prefer variety in the products. Cutting the costs and increasing quality are the benefits of modularization as it imposes less changes in the whole environment of the manufacturing process (Miller, 2005).

A wide variety of results can be generated by combining a limited number of modules. It allows for effective management of knowledge and activities. Introduction of modules in architecture goes back long in history and is not a new concept. Almost in every design the idea of module as a measure of length is used. By trying different combinations of building blocks some variety in the designs is created. A module has to have a certain distinct function that is identifiable and significant in the overall function of the product. Definition of modularity depends on functionality while a module is a unit mostly physical but in some cases (like software, etc.) non-physical (Pahl and Beitz, 1996).

The re-use of modules preserves and uses the already-gained knowledge in the firm and helps in keeping the prices low and schedules running fast (Sanchez et al., 1996).

Design Patterns are the typical solutions that have been proven to be working fine for a problem over time and have evolved in a Darwinistic approach. In fact, modules are structures that contain previous engineering knowledge and by using them all the previous knowledge is gained back again (Anderson & Pine, 1997).

Modularization has emerged in the industry in cases where there's a need for customization while keeping the process simple, so it brings rational production and keeps tasks clear and as independent as possible and increases flexibility (Karlsson, 1995).

Human mind is limited in processing the very broad range of all the solutions that are available and so it is necessary to reduce the level of complexity of the design. Creating hierarchies and breaking down the structures help in identifying each separate component and the designer can then focus on only one solution at a time. It also helps for classifying of tasks and doing them simultaneously and separately and leads to saving time (Alexander, 1964).

There are two important attributes necessary to define modularity, one is that designer must be able to create a variety of combinations within a modular system, and another is that each module must provide independent functionality. It is essential to look at the module and the system in which the module is used and then see if they both meet these requirements. Modules must have compatible mechanical and functional interfaces and interactions so that they can be easily exchanged (Pahl and Beitz, 1996; Ulrich and Eppringer, 1995).

Design for variety methodologies help the design team in coming up with solutions that changes in them will have less effect on the costs in the life-cycle of a product (Martin and Ishii, 2002).

According to Ulrich (1995), an architecture for a product could be considered which shows the physical parts of the product, defines all the functional items, and maps functions to physical elements and also makes the interactions among components more clear. Developing product architectures help the designers to base their design on the existing previous designs and in this way it can reduce the costs of the design process. By understanding the product architecture one can see how to apply needed changes to the previously designed products for the improvements and for the design of new product with the least amount of costs incurred to the manufacturing and design methods. It is worthwhile to always pay attention to the fact that the variety that is being created in the products will generate varieties in the production line. During the course of time, the needs of the customer change, the reliability expectations from the product increases, and so does the demand to reduce the costs of the design and production. Maintaining a competition with competitors, changes in regulations, environmental conditions and changes in the environment of the product, the need for new features, reducing costs and materials and assembly time, etc. can be other factors that impose changes to the design of the existing products. As suggested by Ulrich (1995), it is a good practice to identify the coupled components. Two components are considered to be coupled if changing on of them requires the change of the other one. In fact, while some changes might bring benefits to the design, some other changes that result from these necessary changes (changes in the coupling components for instance) may not be as beneficial.

Generally, in the tradeoff between standardization and modularization, the target is to maximize the amount of standardization in the product platform and in cases that standardization is no more possible modularization is applied. If a component doesn’t require any change or requires small changes, standardization is possible. Drastic changes will require modularization based on the interactions with other elements and if the changes will result in the changes in the other elements or not (Martin, 1999).

In this conceptual design, the modular design has been emphasized, mainly because it is necessary to be able to create a variety of different combinations in a customization process due to the fact that it is assumed from the very beginning that the SPACYPHY units will have multiple purposes and different modules can have the needed functionalities of each use case. Another reason to introduce modularity was to reduce the complexity of the project as the plan was not to design a very specific unit for a special need and then having to redesign from zero for another use case. Lastly, one motive for creating a modular platform was to make use of all the similarities and intersections in the requirements of different use cases to generalize the final solution as much as possible.

Applications of 3D Printing for Rapid Prototyping

Currently 3D printing is widely used for rapid prototyping meaning a quick generation of design prototypes especially in the fields of arts, mechanical engineering, fashion design, jewelry design, architecture, bio-engineering, etc.

The state of the art of technology now allows 3D printing in prototype scales with many different materials including different plastics, combined plastics and wood, steel, paper, ceramics, etc. with different colors and textures. 3D printing with most of the materials available may not have good structural durability and performance but 3D printing with steel and valuable metals can lead to very high accuracy and strength. 3D printing allows very high level of detail and complexity and thus freedom for the designer (ADDLab, 2015).

Bio engineering products and mechanical systems that have high level of complexity are nowadays printed as the final product since they have a relatively small size and scale and therefore the printing machine does not require much material and time for the process.

One challenge that still remains in the process is the support structures that are added during the process of printing and they must be removed after the print. If the geometry is very complex it might be difficult to remove these support materials that are printed with a different material that can dissolve in water or a special solution. So, each 3D printing machine and technology has a different method of cleaning these support structures (ADDLab, 2015).

However, in construction projects architects and engineers are always looking for bigger scale prototypes and technologies for 3D printing them have to be developed further.

In this conceptual design project, in order to get a feel of how the design will look like, so that it can be demonstrated to experts and their comments and opinions in how to improve the design could be collected. Some prototypes were required to be made so that the concept could be introduced in a faster and more efficient way to the interviewees and this could make getting their minds working on the requirements that have to be accounted for in this design easier. Another benefit of creating a prototype was to double check that the mechanisms and movable parts are working fine as intended in the design and as was simulated and checked in the software.

The main motive to use 3D printing as a rapid prototyping technology in this project was that nowadays it is possible to print the whole assembly at once and the device will create a support type of material between the movable parts that can be easily dissolved in water or a special liquid and thus time could be saved by not being forced to print all the parts of the product individually and then assemble them after the print. This, however, is not yet possible with other rapid prototyping technologies like laser cutting, etc. Another motive to utilize 3D printing in creating prototypes was that the design consisted of parts with high levels of detail and as stated earlier 3D printing provides the means to create very complex products.

QFD: A Systematic Approach for Product Development

QFD is a systematic approach in designing a product or service that gives the highest value to the needs of customer and it involves all parts of a corporation. QFD stands for quality function deployment which describes the needs of the customer as quality, how to achieve those as function, and who to do it and when as deployment. The theory was developed first in 1972 at Mitsubishi’s Kobe Shipyard and currently it is being used by Nissan, Toyota, Komatsu, Nippondenso and Honda in Japan and Ford, GM, Chrysler, DEC, TI, 3M, HP, AT&T Bell Labs, Xerox, NovAtel, Exxon and Dow in the United States (Akao, 1997).

QFD brings the possibility to achieve higher quality products, faster and cheaper. It gives a central role for the customer to drive the design and it makes it clear how to develop the design further. QFD brings better understanding of customer needs, reduces organizational errors, reduces the need for changes in the design, improves the quality of the product, and helps to initiate the manufacturing process faster (Warwick Manufacturing Group, 2013).

In this thesis, some useful applications of QFD as a product development technique were examined in Civil Engineering. Buildings are regarded as products, and the owners and inhabitants as customers, and the contractors as manufacturers. It was particularly important to use QFD because the development of the new concept for the design of healthcare facilities was based on the needs of patients and hospital staff (as customers) and it was crucial to determine their demands and then conduct the design in a systematic way so that each of the designed elements and design decisions have a background to support them. In this approach, in developing the concept the designer is not playing the key role, but the customer is. Healthcare is a complicated phenomenon and may not be the specialty of the engineer to deal with all the details that he has to consider, and thus, the designer needs to ask experts for their ideas and this has to be done in a systematic way to reduce the possibility of errors in the design.

The first step in the QFD analysis is to collect the customer requirements. Satisfaction of the customer is the main engine driving a prosperous business. Engineers can’t always put themselves on behalf of the customers because engineer’s own level of expectation is more often than not different than customers. Moreover, it is required to think about a storyline for the use of the buildings and products. Any potential user of the designed product has to be identified. The users most of the time are not simply one group or type of people, rather enough attention must be paid to the chain of different customers that the product is about to have and all of them have different needs and different interactions with the designed solutions. The way the owner interacts with the product is not the same way as the operator interacts or the user interacts. QFD attests that the engineering team must dedicate the requirements of internal customers in favor of external customers since it is the external customer that will be the end user of the solutions and their expectations should not be compromised by keeping the internal personnel, manufacturers, etc. satisfied. When identifying customers it is a must to consider all the people who are potential buyers in the market, whether they are buying the product or they are buying alternative products and whether they are satisfied or not.

In the previous sections the main target groups were introduced and how they were conceived was discussed. So, now was the time to gather their requirements. To do so, there are a few techniques suggested in QFD. It is important to look at the needs of customers in their own words. Questionnaires can be compiled and telephone interviews, face-to-face interviews, clinics, and focus groups could be executed, and also processed data like statistics, company accounts, product reports, news, etc. can also be reviewed.

Subsequently, the technical requirements also known as engineering requirements are needed to be gathered. These are the requirements that customers do not necessarily recognize their existence. These requirements come from technical specifications and regulations.

In this thesis, hospital patient satisfactory surveys were reviewed, design guides of healthcare facilities were checked out, and I tried to gather as much of requirements that I could and finally some interviews were conducted with healthcare experts and their opinions about the requirements of one complete single patient unit was asked. Below you can find a brief list of some of the gathered customer requirements in Table 1:

Table 1. List of Gathered Customer Requirements

Energy conservation shall be considered
Security measures for patients, families, personnel, and the public
Reliable utilities (water, gas, sewer, electricity)
Pollution control laws and associated agency regulations (medical waste storage and disposal)
Equipment should minimize the release of chlorofluorocarbons (CFCs)
Maximum room capacity shall be two patients
Each patient room shall have a window
Handwashing station shall be provided in the patient room in addition to that in the toilet room
Each patient shall have access to a toilet room without having to enter the general corridor area
Visual privacy from casual observation by other patients and visitors shall be provided for each patient. The design for privacy shall not restrict patient access to the entrance
Floor materials shall be easily cleanable and appropriately wear-resistant
Bed must be easily carried to bathroom
Dry work zone must not be visible by patient
Dry work zone has to be in a proximity to head wall

Clean linen supply must have a storage place under the dry zone
TV and remote monitoring devices
No windows should be placed between units
Unit has to provide headlights above the bed
Unit must have a chair for the nurse
Unit must have internet connection
Each unit must have its own lights
A telephone is needed near patient
Clothes hangers are needed inside unit
A space is required for additional health devices to be brought into the unit
Inside the unit must have a nice looking façade to create a calm atmosphere for each patient
Patient needs to be entertained by a TV, book, game, his laptop, etc
Each unit must have a trash bin
Furniture are provided by the unit
Modules have to be suitable for 3D-Printing
Indoor air quality must be measured and amount of CO_2 must be controlled
Handwashing facilities, with other than hand controls, shall be provided for each patient bedroom
Each patient bedroom shall have a toilet directly adjacent to it, in a ratio of not more than eight patient beds for each centralized toilet served
At least one centrally located shower or tub within each nursing unit shall be provided for each twenty patients
A nurses' calling system shall be provided
A locker or closet shall be provided for each patient, to be located within or directly adjacent to each bedroom
Provision shall be made for the administration of suction and oxygen to patients, with built-in or portable equipment.
Stainless material needs to be used
Floors and Walls must be washable
The unit must not block the passage of nurses in hospital dorm halls
Space suitable to be accessed by disabled
Each unit must have family area and sofa

Unit must have a bedside table
Unit must have a TV

The next step in constructing a QFD chart is to find how important is each requirement for the customers and they would position this solution in comparison to other alternatives. In other words, in each of the requirements, how well the product is serving to satisfy the customer need compared to other solutions. They can be asked to give a numerical rate of importance to the requirements, and also for how well these requirements are achieved with this product and alternative products. One way to get these numbers is through surveys and then one can make a weighted average of the opinions of customers and experts and input the results in a QFD chart. So far, the engineering team can analyze the areas that are critically important for the customers and the team can invest in them and also can detect the areas where this solution can't perform as well as other alternatives or competitors and they can try to improve it.

In this thesis, in interviews surveys were prepared and healthcare experts were requested to give a rate of importance to different requirements. Also, in the early stages of conceptual design I had multiple concepts in mind and I could analyze in what areas each of them are superior in performance to others.

Afterwards, the engineering characteristics need to be derived base on customer requirements. These, are the specifications that should be met so that the customer requirements are fulfilled. Engineering requirements define a set of measurable parameters that need to be optimized so that the product can have different functions and can help in achieving one or multiple customer requirements. Engineering requirements convert the customer requirements into measurable items that can be optimized and they facilitate quality control. So, by looking at design guidelines of hospitals and healthcare facilities many of these engineering requirements could be found as well. For the detailed design of the concept, however, a cooperative work of experts is desirable from different engineering disciplines to enlighten how to achieve different certain customer demands. Then, the engineering team can examine and measure how well the solution fits with the engineering standards and comparisons can be made with the competitor's products in numerical and measurable terms. In this research, the different design alternatives that were in mind were compared in different engineering characteristics to see which one to select and proceed further with.

Next step in the QFD analysis is filling the relationship matrix to correlate the customer requirements and engineering requirements. So, the relative strength in each relationship is determined and marked in the sheet. Also, the relationships between each two engineering characteristics should be defined which can be a negative or positive interrelation. This means that in some cases maximizing a certain engineering characteristic can lead to minimizing another and they are conflicting with each other. In this way, in fact, the negative effects of changing particular parameters in the designs are perceived. Moreover, how and through which engineering characteristics one certain customer requirement is being achieved are being clarified.

Next, a minimum value, a maximum value or a target value can be determined for each of the engineering requirements to be achieved. Also, in QFD analysis, the related engineer or expert can determine how difficult it is to achieve each of these targets. So, a valuable outlook on the areas that are important for the customers are gained and they can be improved if necessary. The relationship matrix can determine automatically the importance of each of the engineering characteristics because they are directly linked to customer requirements and their importance.

After completing a QFD chart, its analysis yields to developing the design further. The spots where this design perfectly suits the customer demands, the areas where the product is offering a better solution than others, and areas where the design lacks competence and must be improved are identified. With all of the team members involved the group can go through each row and column of the chart and discuss the possibilities and ideas to further develop the design (Warwick Manufacturing Group, 2013).

Below you can see an example of a completed QFD chart:

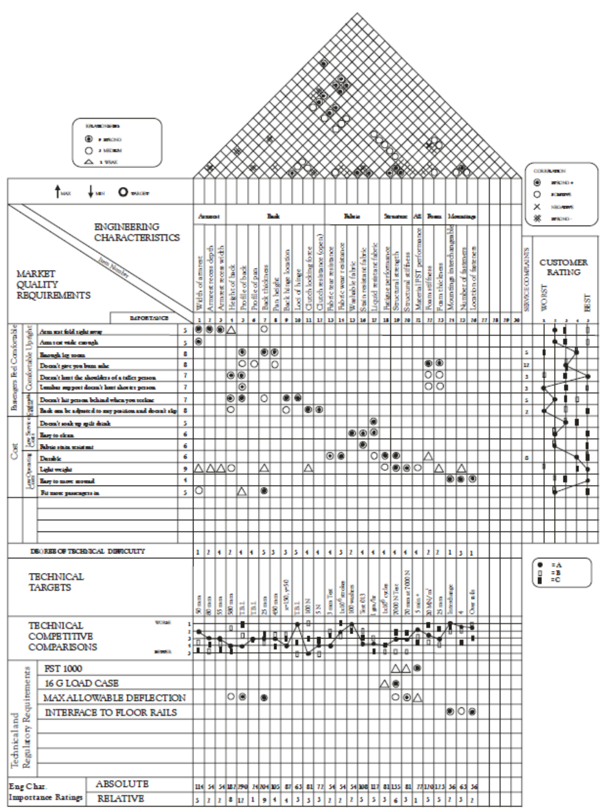


Figure 9. A QFD Chart Example (Warwick Manufacturing Group, 2013)

QFD, can have very positive effects and applications in the design of built environments, too. It can be used right after the early concepts are developed. Since Civil Engineering projects have a vast variety of users and are multi-disciplinary the application of QFD will help in identifying the needs of end users, organizing those needs and linking them to design specifications and helps to organize design specifications and identify the supportive or conflicting roles of each engineering requirement. However, looking at the project as a whole requires simplifications and generalizations so that it can fit within the realm of one QFD analysis. The methodology that is suggested here to be used in the design of buildings or infrastructure is to breakdown the project into multiple parts and sections and conduct QFD analysis for each separate section and then conducting a generalized QFD analysis for the whole project to link and analyze the relations between these sections and tasks.

In the following sections of this thesis we will describe how QFD was used in this conceptual design project as a sample to demonstrate how it can be used in Civil and Structural Engineering.

Structure Sharing in Design: Bringing Resource Effectiveness into Play

One of the methods in product design to make a product more resource effective is structure sharing. It is achieved when the same structure is expected to perform multiple functions. The concepts of function sharing, structure sharing, function combinations and integrated structures have long been used by designers either consciously or in some cases unconsciously to design more resource effective and more creative products. However, it was not until recently that the works of researchers strived to create fundamental methodologies to help better understand the process of the design of such products. There has been ongoing research for developing some methodologies to apply structure sharing in the design and assess the resource effectiveness to come up with cheaper and more innovative products. Structure sharing is one of the methods of sharing in product design. There exists other types of sharing such as function sharing, structure redundancy, and multi-modal integration. In function sharing, several structures are contributing in achieving one function. Structural redundancy has been used when the designer provides multiple structures that each is enough to fulfill the same function. Lastly, the cases in which one structure can have multiple functions is called as multi-mode integration (Chakrabarti, 2001).

Structure sharing in principle creates a trade-off between resource effectiveness and changeability of the product parts. The more the sharing in the design, the more cost and resource effective will be the solution, and the less easy to change will be the assembly parts where there’s a need for change in cases of damage, reuse, disassembly, etc. Nevertheless, in the design of many products resource effectiveness is extremely crucial as its effect on the overall cost can be huge and save of materials is necessary (Chakrabarti, 2004).

Aerospace is one of the areas in which structure sharing has been widely used because of the mentioned reason. Also, today there's a trend in the design of products to add as many features as possible to one single product, making it portable, handy, light, and multi-purpose. In the design of multi-purpose products structure sharing has had a widespread use (Chakrabarti, 2004). In the area of built environment and construction and architectural design, the reduction of spaces needed can lead to sharing in many ways. Using one space for multiple functions can be categorized under structure sharing, where the structures are the physical components of the built environment that is being designed and constructed (walls, columns, beams, concrete, reinforcements, façade, glass, etc.) and the functions are how these spaces will interact with the end users and the qualities they must have to fulfill the main purposes they are being constructed for. By bringing the concepts of sharing in the architectural design, more innovative approaches can be sought in design of buildings and infrastructure in a way that more functionalities are achieved with the same amount of construction materials and labors used and also more spaces can be saved and by getting into other use the available spaces when it is not needed for its main use one can reduce the waste of space in the design.

Thus, creating methodologies to create a decision making framework for the designers can be of high value. In this thesis, after developing a computational method to assist the designer in his/her decision making the approach was implemented into a computer software to automatically do the calculations while the designer is focusing on the different design alternatives. The software can be also integrated in BIM environment where most of the architectural and structural design takes place in Civil Engineering and Architecture areas and the software can capture the structures that are involved in the design automatically, making the process of computational analysis faster and less error prone.

In this thesis, structure sharing is a matter of interest because now that there will be technologies like direct digital manufacturing in hand, designers are free to create more innovative design solutions. Nevertheless, it is important to follow systematic methodologies to decide on structure sharing. In other words, sharing the structures with the availability of more advanced technologies like 3D printing will not cause any manufacturing difficulties and it can easily bring resource effectiveness, but the designer should be cautious about the degree of structure sharing.

Previous works of researchers point out the importance of the level of abstraction in which the structures and functions to be shared are being analyzed. They could identify existence of structures, functions and sub-functions, organs and behaviors in one product. Previous research suggests that when a group of physical effects are creating a principle, the total number of possible combinations of schematics with and without functional overlapping can be calculated as:

$$2^{(n-1)} \tag{1}$$

Where, n is the total number of physical effects used in the principle. This creates a solution space of all the different alternatives where structure sharing can take place between different effects. However, in some cases functional overlapping between components cannot be easily detected and there might be an overlapping range value and degree of overlapping other that merely stating whether functions overlap or not (Chakrabarti, 2004).

One of the best efforts in the existing literature for developing computational framework for structure sharing is done by Ulrich (1988) where function-sharing is boosted by deleting the unnecessary elements in one solution and by checking whether the rest of the components can still fulfil the functions of the deleted component. By running loops of this analysis one can optimize the designs by reducing the number of structures that do not play a central role in achieving the intended functions. One computer software goes through all the structures that are taking part in one design solution and checks one-by-one if they can be removed from the design. However, this method is working in a geometric environment meaning that the concept must be already well developed and the geometrical solution of the concept must be in hand for the method to be used which can create challenges in the early phases of conceptual design. Also, it is not very reliable to expect the software to identify all the mutually dependent structures that deleting one can disrupt the performance of another.

Other research work done by French (1992) defines some constructs to be used to create solutions which satisfy a given function, namely variables, properties, constraints, effects and components. Then by implementing an algorithm in a software one can generate many possible alternative solutions by first identifying the properties needed for achieving a certain effect and then searching up a component database for all the components that have such properties followed by generating solutions and removing the extra components to achieve highest level of structure sharing. This methodology can be very helpful in the design of products where it is feasible to collect a database of components and their properties to develop alternative solutions. However, the methodology doesn’t propose any approaches for evaluation of the results generated by the method. In this thesis, a measure have been developed for computational evaluation of structure shared products and by utilizing this methodology one can eliminate the unhelpful generated results of the discussed methodology and reduce the number of solutions in the solution space so that the prototyping, testing and final selection of the best solution would become more efficient and faster.

In here, the definitions that are used for functions and structures are presented and methodologies that are currently in use to identify the structures and functions in the design and to estimate the resource effectiveness of a design alternative are proposed. By reviewing the literature in the structure sharing one can obtain an acceptable general definition for function and structure. Main function of a product is defined as the expected effect from the product. However, the product will have multiple other functions that are helping to achieve the main function and they do not necessarily have a high relative importance for the users. A product is formed by a collection of various items (Pahl and Beitz, 1996; Otto and Wood, 2001; Ulrich and Eppinger, 1995; Lindbeck and Wygant, 1995). A product can be looked at in a function related perspective or in a structure related perspective (Andreasen 1980; Andreasen, 1992; Hubker and Eder, 1988). In principle, functions are the effects that are observed from a product and structures are the physical means that are bringing those functions. To identify all the functions and structures that are taking part in shaping a product, a systematic approach known as constructing the function-means (FM) tree is used. In this method, starting by the main functions that are expected from the product the designer breaks it down to the components that are providing the means to achieve that function. In the assessment of resource effectiveness and the degree of structure sharing identifying the structures and functions play a central role and it directly affects the results of the estimations. One of the most important concerns related to identification of these functions and structures is the level of detail that a design solution is being investigated at (Hubker and Eder, 2001). As the aim is to develop methodologies that are universal and are not having subject dependent results, it is needed to make it clear what the expected level of detail that the designer is looking at the product must be. One of the measures that is developed to help the designers in determining how innovative and resource effective is one solution is the degree of structure sharing. It can be calculated by the following equation (Eq. (2)):

$$\text{Degree of SS} = \frac{\text{number of functions at the lowest level of abstraction}}{\text{number of structures}} \tag{2}$$

According to the formula above the higher the number of all the different functions, and the lower the number of structures that are used in the design, the higher will be the degree of structure sharing. In this formula the total number of functions of a product in its operating environment is used to make it clear for the designers. Functions are the effects that are expected from different components. It has been taken into account the fact that each structure can have multiple functions. In the denominator of the above formula the number of any independent physical component that can be identified is counted and inserted. Also, the industrial processes in the manufacturing (like bending and making cuts and holes) should be considered as a structure (Chakrabarti and Singh, 2007).

Now let's discuss the methodology in constructing an FM tree. First, the designer should determine all of the main functions that are expected from the product. For each main function it is required to produce a separate FM tree. Then, proceeding to the next level the designer thinks about how this function has become possible and what are the processes and sub-functions and structures that are involved. Each branch must be made as detailed as possible and the process continues until a structure is reached. With this method the designer can make sure that he/she has identified all the different structures and afterwards he/she can easily count the end points of each branch to determine the total number of structures in one design solution. Sub-functions are the functions that merely satisfy the requirements of another higher level function (Chakrabarti and Singh, 2007).

Here is one example of a constructed FM tree for an electric light bulb for the purpose of demonstration (Fig. 10):

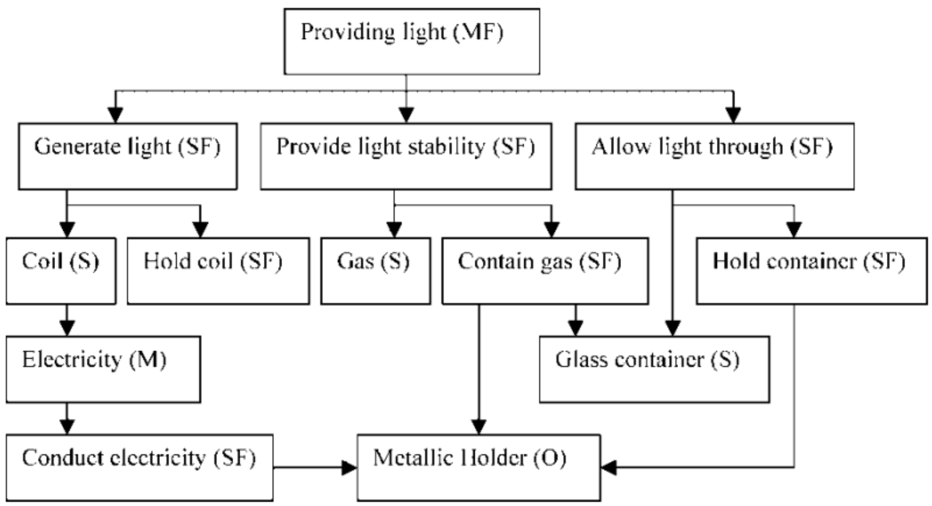


Figure 10. Example of a FM tree for an electric light bulb. MF=Main Function, SF=Sub Function, S=Structure, O=Organ (Chakrabarti and Singh, 2007)

In the literature it is stated that the resource effectiveness always increases by increasing the degree of structure sharing (Chakrabarti and Regno, 2001).

Another measure that has been developed to help the designers in estimating the degree of resource effectiveness, defines the resource effectiveness as the ratio of number of main functions to the number of structures that help in achieving those functions:

$$\mathrm{RE} = \frac{\text{number of main functions}}{\text{number of structures}} \tag{3}$$

The main functions are defined as the main effects that are the purpose of the design for the whole product. Each product might have multiple main functions and each will form a separate FM tree. A Swiss-army-knife as an example has many main functions and each of those are independent from each other and will result in a new FM tree.

Previous research in this area has proven that by reducing the number of structures involved in providing one functionality, the cost effectiveness and efficiency are being improved. It suggests that simpler designs that have less sub-functions and structures will be more resource effective. So, by drawing one FM tree one can easily derive the values of RE and SS and they give measurable and comparable values for analyzing different design options.

Here is an example of estimations of SS and RE for the sample electric light bulb product:
There are 4 functions at the end points of the branches and 3 is the total number of structures. So, using Eq. (2):

$$SS = \frac{\text{number of functions at the lowest level of abstraction}}{\text{number of structures}} = \frac{4}{3} = 1.33$$

Similarly, using Eq. (3) we can derive the value of resource effectiveness:

$$RE = \frac{\text{number of main functions}}{\text{number of structures}} = \frac{1}{3} = 0.33$$

Also, in the literature it is suggested that to make sure that the FM tree is complete, one can make a bill of materials as follows (Table 2) and double check that he/she has included all the structures:

Table 2. Sample Bill of Materials Table

Sl.no.	Assembly Components Structures	Quantity	Function (S) corresponding to each structure	Materials and manufacturing process

By looking at other methods of performing a function, the designer might be able to reduce the number of structures and consequently reduce the amount of materials and resources. If there are features that are common between different structures in one FM tree, there might be the possibility to use the same feature to generate multiple functions. Also, overlapping features in different FM trees of a single product can be found. The manufacturing processes should also be taken into account and it should be tried to reduce the variety of techniques that are utilized.

These measures, however, do not take the quality of function into account. Quality of function determines how well the function is being performed, and has direct impact in the end user's satisfaction of the product. In this thesis, one goal has been to improve these measures by accounting for the quality of function, too. In the next chapter we will discuss further how a new measure for estimating the effectiveness of structure sharing was developed. Also, in the developed measure the negative effects are taken into account. Also, a methodology for utilizing the additional sub-functions that are created in the design and are not used for the purposes of the design is put forward. Furthermore, the definition of a structure in a perspective that also considers manufacturing difficulties will be discussed.

Direct Digital Manufacturing: Can the Emergent Technologies Be Counted on for Mass Production?

The manufacturing techniques and buildability of the product was another aspect that was taken into account. Therefore, by looking into the newest available manufacturing technologies it was yearned to help improve the design in such a way that it suits the production technology of choice. The particular interest was in direct digital manufacturing technologies, since they are newly emergent technologies and they suit the purposes of manufacturing modular designs and parametric designs. In addition, apart from the purposes of the conceptual design in this particular project, the limitations and opportunities that direct digital manufacturing techniques in product design and development (and similarly direct digital construction techniques in Civil Engineering) will impose on the world of design were investigated. In other words, by assuming that there will be a day that the most efficient and accurate direct digital construction technologies are in hand, the ways that the designs of engineers and architects can be affected were explored (Hölmström, 2015). In this research methodology the initial step was to case study successful applications of direct digital manufacturing techniques in the construction industry as of today, and the second step was taken by drawing an analogy between the designs and manufacturing that are happening successfully in other fields, and those that are expected to form in Civil and Structural Engineering.

Assuming that the most advanced direct digital construction technology are available, there will be drastic changes in the design phase in construction projects. Joints between elements can be reduced as companies may be able to 3D print bigger modules requiring less joints between them. However, the less number of elements and joints in the design scheme, the harder it will be to maintain it, repair it and change it in cases of damage. Also, structural systems can change and there will no longer be a need to design conventional beams and columns as structures, rather very high level of detail structures like steel meshes and Nano-structures can be developed which will lead to the save of material and resources. Designers are free to design freeform shapes and complex geometries which have artistic magnificence without being afraid of the manufacturing technology which is limiting their choices. Façade systems can change as they can have high detail textures. Each element and module can have unique shapes and standardization will no longer provide a significant benefit. The design can be modified and improved immediately after a dissatisfaction report because there is no longer a need for the changes in the production line which used to be very costly. Very complex shapes and patterns can be brought into the design of built environment since there will no longer be the limitations of difficulty of execution and this will lead to greater aesthetic values. The total weight of the structure can be reduced by designing cavities inside solid elements and this will lead to less self-weight loads that requires less structural robustness and total amount of materials used will be reduced.

Case Studies

In this section of the thesis, we summarize the results of the case studies that were done in different areas that were related to this project. Each of these case studies could contribute to the overall understanding of the problems and opportunities that can rise in this project because of the similarities to the studied cases. Using CNC laser cutting technology in the design and manufacturing of single family houses in Finland were studied to see whether DDM technologies can fit the needs of this project and what can be the limitations and possibilities. Similar healthcare projects that involved the design of pods and units for the improvement of healthcare services were studied to be able to make use of their findings and avoiding the problems that were faced in those projects (Bioquell Pods and Rem Pods). Finally, similar projects that are being conducted in Finland and at Aalto University in particular were studied to see their scopes and visions so that this project can fit in purpose to those projects. There were some other projects and cases that were studied but enough similarities to this research were not found there, therefore, they are not mentioned here.

Case Study: Applying CNC Laser Cutting Technology in Building Wooden Single Family Houses in Finland

One of the successful applications of DDM technologies has been the manufacturing of single family wooden houses in Finland. Architects begin with modeling the walls and windows and doors as components in the BIM environment and by using ArchiCAD API they can convert the walls into individual logs. Joints between the logs are automatically calculated and drawings are generated. The position of drillings can be designed and is automatically marked in the drawings and also an ink jet printer marks the position of electric drills on the logs. Each log in the software has been assigned one unique ID value. It is possible to customize the automatic generation of individual logs, too. Software takes into account logistic issues like the maximum length of logs to be transported by trucks (6 or 12 meters). There are many different types of joint types, door types, window types, specific to the products that are used that can be imported in ArchiCAD project and used and they are parametric models so it is easy to change the parameters and customize it to be used for the particular design of the architects (MAD, 2015).

The software creates a CNC file and this will be delivered to the manufacturer where they can cut the logs using their CNC machines and mark them using ink jet printers to make it easy for assembly. There is no need for huge warehouses and storage spaces.

Each house can be modified easily and redesigned inside the software and customized to the favor of the end user. On the contrary, in the conventional methods changing the design would have required much manual work (creating drawings again, etc.) that couldn't make it beneficial. But now, with automatic generation of all the drawings and CNC codes, etc. after every change the quality of the design can be improved by necessary alterations.

It is possible to easily create a light model to be executed by smart phones and tablets for the end user to access the model, all the drawings, and all the needed information related to the building.

Another advantage is the reduction in the number of software that different parties in the conventional design methods were using to access and change the model but now it is for instance possible for the manufacturing company to open the CNC code in their software to look at the 3D geometry and do the calculations for the lifting and manufacturing process.

There has been cases that the same method has been used to generate joints to connect concrete prefabricated elements using CNC technologies. However, because there have been complexity in the design of joints and many parties to be involved (architects, engineers, prefabrication company, manufacturing engineers, manufacturers, etc.) and the amount of work to be done by limited engineers of the manufacturing company and also the software packages being limited to few and not available to be developed further, those projects didn't turn out to be economically beneficial and thus were given up by the developing company.

It is also possible to send each individual log as an STL file to be 3D printed. One challenge in creating CNC files is that different manufacturers use many different machines, each having their unique syntax and language for the CNC files and thus the design software has to be compatible with multiple machine syntaxes beforehand.

The company HONKA has had the biggest projects of wooden log construction in the whole Finland in which it has applied these techniques successfully.

After all, one of the biggest challenges that currently exists in the developments of these direct digital manufacturing technologies is the fact that it is difficult to directly manufacture multiple materials at the same time. This needs to be developed further until it can be affordably applicable. Thus, it is still not clear for us whether direct digital construction techniques are the fastest and most efficient techniques to be used in this project to build the SPACYPHY units. In one hand, modules were designed with a high level of geometric detail and complexity that makes it difficult for manufacturing it with conventional methods, and on the other hand if it is decided to stick to direct digital manufacturing techniques as the only manufacturing process there will be limitations in the choice of materials for the design. This can be decided after that the detailed design phase of the project is done and the team is sure about the selection of materials that are used in the product. One solution might be to mix conventional technologies with DDM technologies and to utilize automation to a certain level. This, however, needs further research.

Case Study: Bioquell Pods in UK

According to UK department of health new hospitals that are being built in UK have 50 percent single rooms but most of the existing hospitals have less than this amount. This has the disadvantage that infected patient carrying hospital pathogens have to be kept in multi-bed dorms which imposes a high risk of infection transmission. And two thirds of the surveys reported insufficient isolation facilities in the hospitals demanding for more single rooms. Bioquell has designed a Pod which has all the advantages of a single room. The pod creates a semi-permanent space inside a bay or open ward and it has an internal air flow system that creates a negative air pressure inside the pod. These pods create more single room space for infectious patients and in this case there would be less need to prioritize patients. They create privacy for the patients who prefer private rooms and also they made the observation of patients and monitoring less staff demanding. Another benefit of these pods is that they can provide the same standards of specialist room cares as it was not the same with traditional single rooms.

According to the designer’s claims, the pods are suitable for patients that carry pathogens including MRSA, VRE, ESBL, CPE, influenza and RSV. The air is being filtered before entering the pod and the pod has negative air pressure inside. So, in cases that the hospital doesn't have any more single room to offer to incoming infectious patients and has to keep them in a dorm, using a pod installed in the dorm reduces the risk of transmission of the infection to other patients in the dorm.

Privacy is a high value for many patients especially the elderly ones. Interactions between hospital staff and patients are improved in private rooms and reduced amount of noise gives better quality of sleep for patients and can reduce their recovery time. However, the limited number of single rooms in current hospitals has forced the hospital staff to give the first priority to more infectious patients in allocating single rooms and privacy comes second in priority. Bioquell pod designers claim that they can create a space with more privacy and dignity for patients and their family members. Also, clinical needs of the patients can be fulfilled in the pods that are installed in specialist wards and this will cut off the need for patient transfers. Infectious patients that need to be admitted in a single room and they also need clinical care can be admitted into these pods that are installed in specialist wards and in this way they receive the treatment needed while the risk of infection transmission is reduced. Placing patients in single rooms also requires more hospital staff for one-to-one monitoring and visits, but providing the pods in wards makes the visits and monitoring less staff demanding. Keeping the patients in wards also has the benefit of social contacts and better management of patients. So, usually there's a balance in the design of hospitals between the numbers of wards to single bed rooms. All in all, the pods are said to have the advantages of single rooms and wards mixed (Bioquell, 2015).

However, detailed measures about the degree of satisfying the hospital requirements and also the quality of service and functioning of the pods were not clearly stated in the designer's report. Also, feasibility of installation of these pods and technical difficulties are not discussed. It might be soon to compare the concept of these Bioquell pods to the presented concept. But, methodological differences are clear in the design of those pods and in this project. In this thesis, a broad approach has been followed in collecting customer requirements and making sure they are all fulfilled simultaneously. However, almost all the advantages that the designers of Bioquell pods have claimed to achieve, is also being achieved with the presented concept.

Case Study: Rem Pods

Another innovative solution to help patients with dementia are called Rem Pods or reminiscence pods. They create a therapeutic atmosphere for the patients suffering from dementia and makes them feel calm and in this way there's no need for changing the decoration of their homes to suit them. They help to improve the social interactions between patients and hospital staff by creating a fun environment with a variety of different designs (RemPods, 2014).

The similarities between this project and this thesis project lies in the idea that this thesis is also aiming at providing customizable care units for different patients with different diseases including mental and physiological disorders. With the solution provided in this thesis it will be possible to customize the interior design of the unit and the furniture to suit dementia patient.

Aalto Health Factory – Looking at Current Problems in the Health-Care Based Research

Aalto health factory seeks new opportunities to improve the quality of health services through research and collaborative work. Aalto health factory group believes that the delivery of health care services is broken in some cases and the current state-of-the-art of health services is not a sustainable one. They believe that the amount of waste produced in the current health services is still unacceptably vast and the main reason behind it is that it has not been developed based on scientific research. They promote health care research works that can lead to the development of new models that can deliver more efficient outcomes while maintaining lower costs. According to Aalto health factory, the current links between scientific research works and the health care business is not promising and the current research works are not targeting towards the development of new health care solutions and products useful for the existing health care companies. They state that due to the limited amount of funding especially at the proof-of-concept stage and piloting stage, there exists a gap from problem based innovations to the commercialization of new products. They promote applied research and they claim that they help to fill the existing gaps. This research project is well suited with the targets of the Aalto Health Factory since this research aims to develop a new concept for improved health services. However, in this thesis the focus will be more on the ideation and requirement analysis part and particularly more on the design aspects of the space needed for the solution. I hope that the path of this research continues up to piloting the concept and spinning new companies and finalizing the product. It is important to note that the integration of other health-care based research projects with this project is considered. Having looked into the ongoing projects of Tekes and Aalto Health Factory a concept is being developed that is compatible with the results of those research projects as well (Aalto Health Factory, 2015; Tekes Smart Solutions, 2015).

CHAPTER 3: Conceptual Design of the Product

In this chapter, the course of conceptual design of the product is briefly presented which included different steps that are discussed.

Market Analysis Phase: Who Can Be a Potential Customer?

In the very early stages of the design that I was looking at the customer requirements I decided to focus on the requirements of the most willing customers to use the solution and thus I conducted a market analysis to see how big the target markets are, and what can be their influence and feedback.

These potential markets for the SPACYPHY units were identified: Hospitals that have multi-bed wards and dorms, the elderly that need special care and they prefer to be kept in their apartments, long treatment duration patients to be kept outside hospitals, and finally providing sanitation facilities and satellite healthcare facilities for the regions of the world where enough infrastructure doesn't exist or is costly. Other markets (like units to be located in airports, etc.) have also been recognized that may not have the significance of the named markets and their requirements may be hard to meet in a single design.

Demographic analysis of different regions of the world were investigated. The elderly population in Finland and Europe was determined and assumed that just a small fraction will be interested in these solutions. Based on demographic statistics there are nearly 654,000 people over the age of 60 in Finland and 16.81 percent of the population in Europe and 7.9 percent in the world is over the age of 65 (European Hospital and Healthcare Federation (hope), 2014).

I also looked at the design of hospitals and statistics on how much in proportion are the ones that are comprised of semi-private or non-private spaces like dorms or wards. There are 275 hospitals in Finland and out of 18551 total number of hospital beds in Finland, 11872 are not private. There are nearly 20,000 hospitals across Europe and nearly half of the hospital beds in Europe are not private (The hospitals in the 27 European countries, 2011).

The concept will allow them to turn their wards into a number of private spaces for single patient care. Also, other regions of the world with healthcare related issues and those parts where people lack the access to sanitation facilities have been under consideration. That market is the biggest amongst others since according to the statistics a total world average of 39% do not have access to sanitation facilities. The aim is to lower the final price of the product as much as possible with resource effective methods of design so that the product is affordable for the less economically glorious countries that have well-being and health related issues.

As a basic market analysis, it was tried to estimate the approximate market size for the final product. For that purpose different trends and markets in health-care industry were looked into. The finances regarding current health-care facilities and their maintenance and the need for the new ones and the infrastructure for that were studied. The relative number of single-bed hospital rooms to multi-bed hospital rooms were estimated in Finland, in Europe and then globally. Also, the elderly who need special care was targeted. So, by regarding the growing number of elderly population in Finland, Europe and globally, they were included in the target market. Another market that was in particular interest was the people living in the regions of the world in which they still don't have access to sanitary facilities. From the estimated market it was assumed that a very small portion will be willing to buy the product and thus the market size could be estimated.

In table 3 below you can see the estimated market size for the product:

Table 3. Market Size Estimation for the Product

Number of hospitals in Europe	20047,5
Number of beds in Europe	4046625
Number of Multi-Bed portion of beds in Europe	2589840

Number of hospitals in Finland	275
Number of beds in Finland	18551
Number of multi-bed in Finland	11872

Units Sold

Ratio	5 %

Finland	594
Europe	129492
Worldwide	901744

Ratio	5 %

Over 65		Their own home
		82 %
Finland	653363	535757,66
Europe	124898300	102416606
World	5,767E+11	4,72894E+11

Units Sold

26788
5120830
23644700000

Story-board and Use Case Analysis

Every stage of the lifecycle of the product were analyzed and all the potential users for it were detected. Then, their needs and how they would interact with the product were thought of. The functions that would best fit their needs and how that occurs were investigated. A story-board was created depicting different stages from the design and manufacture of the product to the installation and then to the all different use case scenarios. The main users of the product and their basic needs were identified and incompatibilities or difficulties in achieving each requirement were searched for. So, at this stage a list of the relevant customer requirements were made. Starting with the best guesses and continuing by looking into health-care facilities guidelines as many customer requirements as possible within the timeframe of this thesis were gathered.

Here's a photo of the created storyboard (Fig. 11), similar to the storyboard that is used in the film-making industry to picture a view towards an idea:

Figure 11. Storyboard of the Product

Technical Requirements through Literature

The design must take into account the effects on different user groups with different diseases. It must follow general and local design codes and it must comply with all the regulations of the target country or state. For instance, in the US, in many states the ‘Guideline for Design and Construction of Hospitals and Health Care Facilities’ published by ‘Facility Guideline Institute (FGI)’ is used as an approved source. By looking into different design guides for hospital design or design of health care facilities some of the most important requirements that were reappearing in many guides were summarized:

- The layout of the room must shorten the travel distances for nurses so that they can spend less time walking and they can deliver faster care. So, functional adjacencies must be considered (Vos, Groothuis, and van Merode, 2007; Hughes, 2008; Carr, 2011).
- The size of pods must be big enough to assure possibility of comfortable gatherings of more than one person. The similarities between the designs of different pods must be as much as possible so that nurses and staff can adjust in a short time to new pods (Harale, 2010).
- If bathroom is located inside the room it has to be close to the head of the bed. Handrail supports, built-in sinks and individual lighting switches must be provided inside each single patient unit (Reiling et al., 2004; Ampt, Harris, and Maxwell, 2008). Patients must have free choice for the artwork and decoration of their room (Hathorn and Nanda, 2008). Storage area for the belongings of patients must be provided and a family zone should be designed for the family of patients to stay which can be inside the single patient room (Carr, 2011).
- The materials that are used for construction must have protection from fire and they must be environmentally friendly (USAGE, 1997).
- The design of HVAC system must take into consideration the noise reduction principles apart from the infection reduction principles (ASHRAE, 1995; Peppin, 1997). WHO is limiting the maximum sound level of 0-40 dB in patient rooms at night (WHO, 2007; Solet et al., 2010). Since there is a direct correlation between ventilation systems and airborne spread of infection the design of HVAC systems should maintain a negative air pressure inside isolation rooms (Tang et al., 2006; CDC and HICPAC, 2007; Li et al., 2007; Eames et al., 2009; Tunga et al., 2009; Zhao et al., 2009; Balocco and Lio, 2010). In the US, CDC guidelines recommend that airborne infection isolation rooms must have a minimum of 12 ACH (equivalent to 80 l/s for a 4x2x3 square meters room). Also, the room must have an exhaust to outside or a HEPA filter if the air in the room is recirculated (CDC, 2003). ASHRAE suggests that filters should be MERV 8 + MERV 14 in patient rooms.

- According to AHRAE HVAC design guide for health care facilities, temperature of the patient rooms must be kept between 21-24 degrees Celsius. However, research shows that the most convenient thermal settings can be achieved using controllable thermal systems that allow the temperature to vary between spaces in time (Parsons, 1991; Orians, 1992; de Dear, 2011).
- Windows should be used as much as possible to gain highest amounts of daylight (Ander, 2012; WBDG Productive Committee, 2012) while controlling temperature of the room and taking into account the glare and shade effects (Edwards and Torcellini, 2002; Joseph, 2006; Ampt, Harris, and Maxwell, 2008). Lighting of the room must be controllable via a dimmer switch and light switches must be placed near the entrance to account for emergencies. If daylight cannot be provided, the artificial lighting must be bright to assist the elderly and to aid the staff in performing complex tasks and at night time the lighting must be dimmed enough for providing a better quality of sleep. Guidelines suggest illumination levels of 1500-2000 lx when the age of users increases (Ulrich and Barach, 2006). Lights must be energy efficient and windows must be equipped with curtains or blinds (Dalke et al., 2006).
- Artworks inside the rooms should resemble positive meanings and pictures with landscape, emotionally positive facial expressions, and images of nature with bright colors are preferable.
- Surface material must be easily cleanable and hand washing sinks must be provided inside units to prevent contact spread infections (Larson, 1999; Boyce and Pittet, 2002; WHO, 2009).

Energy Consumption, Green Environment and Resource Effectiveness

In the concept, the SPACYPHY units are smart in the sense that they can detect the idle mode of the system and they will cut off the usage of all the unnecessary equipment and reduce the use of resources. Devices that measure carbon footprints can be installed and the product will be green. Each of the units can be customized to the specific needs of each particular user, so only the necessary devices, lights, switches, and other resources will be used. Also, in the idle mode the unit will shrink in size and allows the space it had occupied to be used for other purposes. SPACYPHY units can be relocated, so the same unit can be used after the need for them in one location no longer exists and this will save material and resources. In the concept, as the design is in a modular way, it will be easy to replace the broken parts of the units or to replace the modules with other modules that have different functionalities. With the existing well-developed communication infrastructure that are mostly portable and programmable a certain level of intelligence can be defined for the designed spaces so that the use of resources can be controlled automatically without the need for an operator.

QFD Analysis Method

Using QFD (Quality Function Deployment) method the importance of each customer requirement could be demonstrated by numerical values. It was also tried to gather functional requirements that can best serve to satisfy each customer requirement. To do so structural capacity requirements, health-care guidelines for space requirements and many other fundamental properties that a single-bed sanitized room must have were explored. In QFD analysis, numerical values were assigned to the level of difficulty of satisfying each functional requirement and the areas where this product can have competitive advantage over traditional solutions by an affordable cost were detected. QFD also provides the means to compare different solutions in the terms of how good they are satisfying the functional and customer requirements. It also, establishes connections between different functional and customer requirements helping to identify the areas that functional requirements are serving or having negative effects on other requirements. So, the level of importance of each requirement in total performance of the product could be understood.

In the table below you can find the technical requirements that were found in the literature and were included in the QFD analysis chart:

Table 4. Technical (Engineering) Requirements of the Product

• Single bedrooms shall be a minimum of one hundred square feet in size exclusive of toilet enclosures, lockers, closets and vestibules
• Patient beds shall not be spaced closer than three feet from each other and sides of beds shall be at least two feet from walls
• Window sills shall not be higher than three feet above the floor and shall be above grade
• Water for clinical use: 6 gallons per hour per bed with temperature of 110 F (11.9 liters 35-43 degrees centigrade)
• Temperature must be maintained at 70-75 Fahrenheit (21-24 degrees)
• Relative Humidity must be maintained at 30-60 percent
• Walls must have enough structural capacity in case of an impact
• Unit modules have to be small and light weight to be transported
• Height must be adjusted to different ceiling heights
• Sink needs to have a tank or needs to be connected to hospital sewerage system
• Walls must be temporarily fixed to the dorm walls while having good isolation

• Walls must have a rolling system that provides best isolation of air, heat, dust while having least corners and spaces for the accumulation of infection
• Walls rolling system needs to be easily cleaned
• Walls have to be easily replaced in case of damage
• the amount of expansion in the direction of the hall has to adjustable
• Unit must comply with Fire Protection code
• Minimum sound insulation between patient room to patient room is 45 dB
• Minimum sound insulation between patient room and public spaces is 55 dB
• Airborne infection isolation room perimeter walls, ceiling, and floors, including penetrations, shall be sealed tightly so that air does not infiltrate the environment from the outside or from other spaces
• Airborne infection isolation room(s) shall have self-closing devices on all room exit doors
• Rooms shall have a permanently installed visual mechanism to constantly monitor the pressure status of the room when occupied by patients with an airborne infectious disease. The mechanism shall continuously monitor the direction of the airflow
• The minimum door size for inpatient bedrooms in new work shall be 3 feet 8 inches (1.11 meters) wide and 7 feet (2.13 meters) high
• Minimum air changes of patient room with outdoor air per hour is 2
• Minimum total air changes of patient room per hour is 6
• Sink must have an extra outlet for cleaning water
• telephone line is connected to hospital telephone line
• Minimum total air changes of toilet room per hour is 10
• Air movement direction of toilet must be: IN
• All air exhaust of toilet must directly go outdoors
• All doors between corridors, rooms, or spaces subject to occupancy shall be of the swing type
• Windows shall be equipped with insect screens
• Glass doors, lights, sidelights, borrowed lights, and windows shall be constructed of safety glass, wired glass, or plastic, break-resistant material that creates no dangerous cutting edges when broken
• Safety glass-tempered or plastic glazing materials shall be used for shower doors and bath enclosures
• Cubicle curtains and draperies shall be noncombustible or flame-retardant

• Materials and certain plastics known to produce noxious gases when burned shall not be used
• Wall finishes shall be washable. In the vicinity of plumbing fixtures, wall finishes shall be smooth and water-resistant
• Floors and walls penetrated by pipes, ducts, and conduits shall be tightly sealed to minimize entry of rodents and insects
• Air conditioning must have filters to control infection: 2 Filters must be used 1 with 30% efficiency and 1 with 90% efficiency
• 1 Station outlet for oxygen, vacuum (suction) and medical air system per bed
• Unit modules have to be light weight to be transported by a normal weight car
• Unit must have a strong floor taking all the variable loads
• Walls must have enough structural capacity to carry the load of the ceiling, snow load
• The unit must fit in one traffic line. It has to be compactable enough
• Unit must be air-conditioned separately from hospital's system
• Unit's water supply must be connected to the hospital's system
• Unit's sewerage must be connected to the hospital's system
• Unit's electricity supply must be connected to hospital's system
• Inside and Outside façade must be customizable

Here you can see the QFD matrix that was completed for the product:

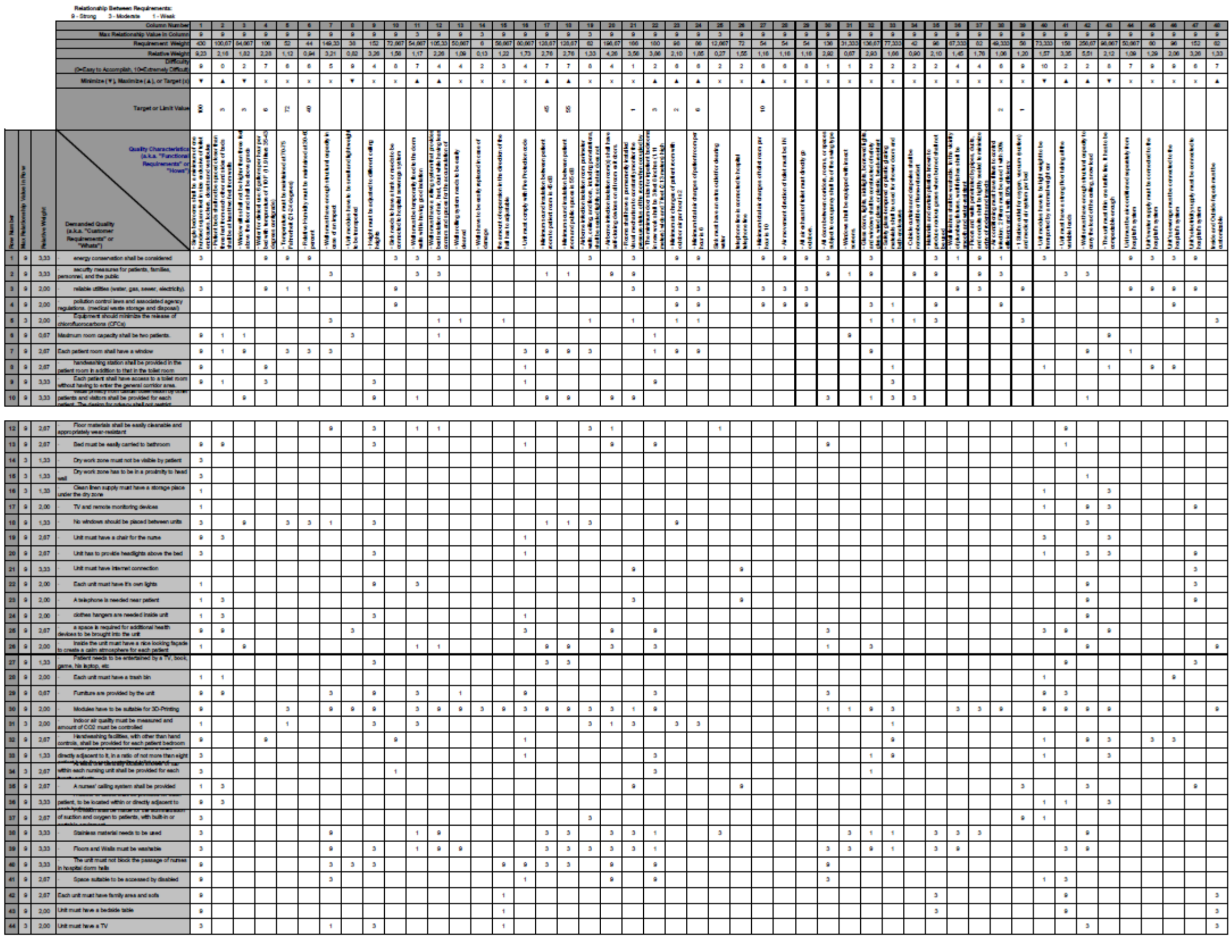


Figure 12. QFD Analysis Matrix for the Product

Initial Design Phase

In the first stage, the very preliminary space needs of the health-care solution were briefly studied and some sketches of many different alternatives for how the space should be formed in a compactable manner were drawn. It was important in this stage to consider some structural requirements of the building blocks of the space that is being created as it would have had dramatic effects on the solutions that were being explored. Later, the basic space solutions were narrowed down to 6 cases that there were in mind that could fit for the basic requirements and for the structural capacities.

Using QFD the performance of these 6 solutions in each functional requirement were rated and by summing the results the best option which was as well dependent on the importance of each of all functions was selected.

In the images below you can see the different design alternatives that were compared to be selected for the expanding solution:

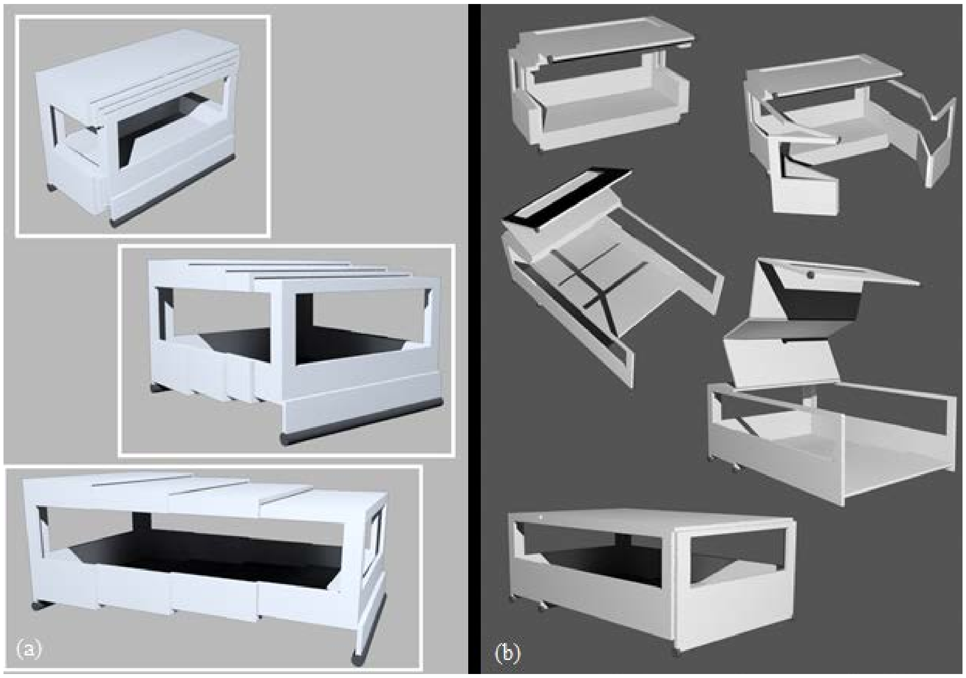


Figure 13. Expanding Solutions: (a) First Alternative (b) Second Alternative

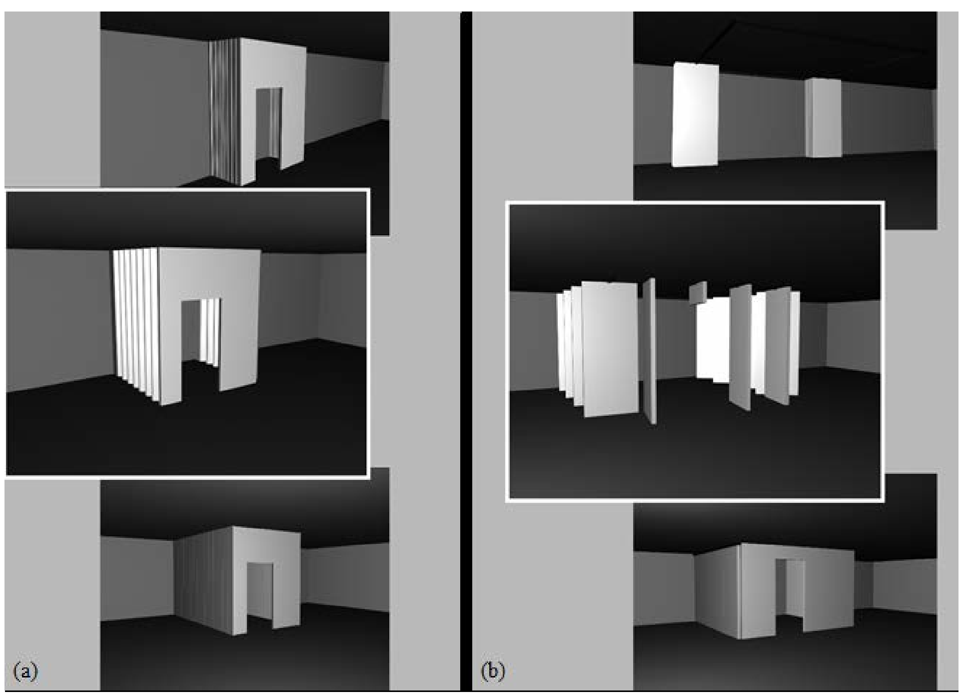


Figure 14. Expanding Solutions: (a) Third Alternative (b) Forth Alternative

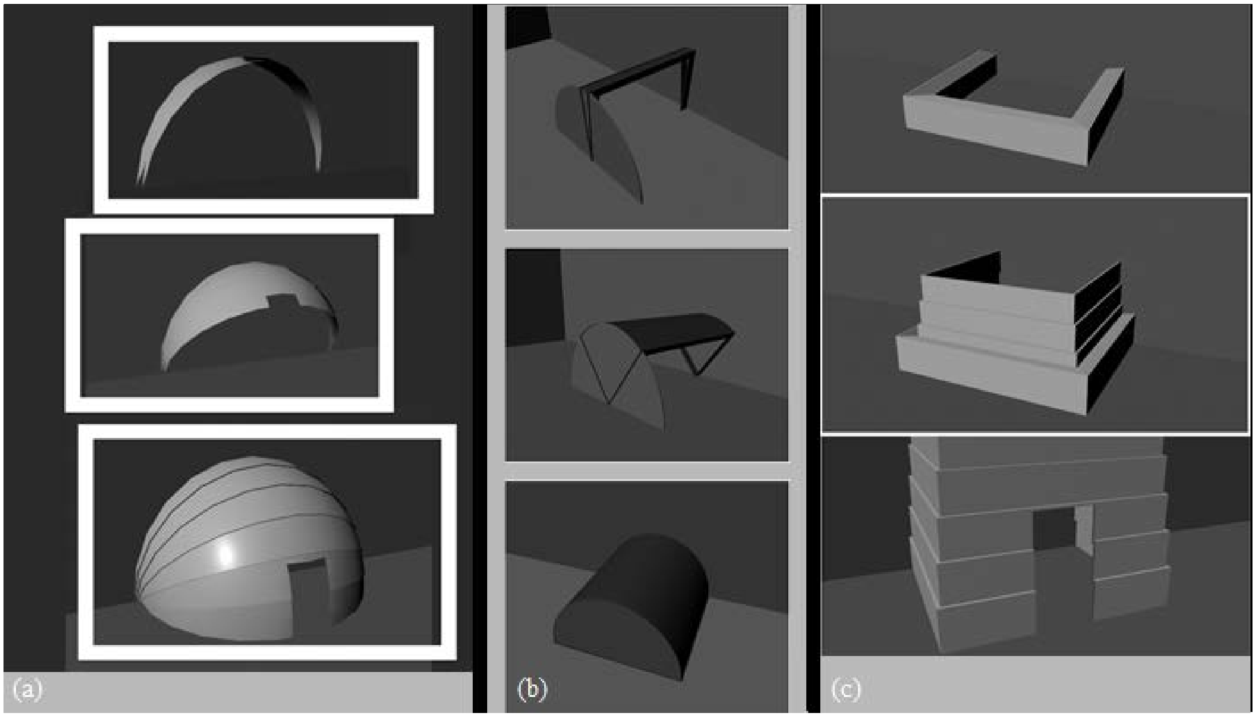


Figure 15. Expanding Solutions: (a) Fifth Alternative Type 1 (b) Fifth Alternative Type 2 (c) Sixth Alternative

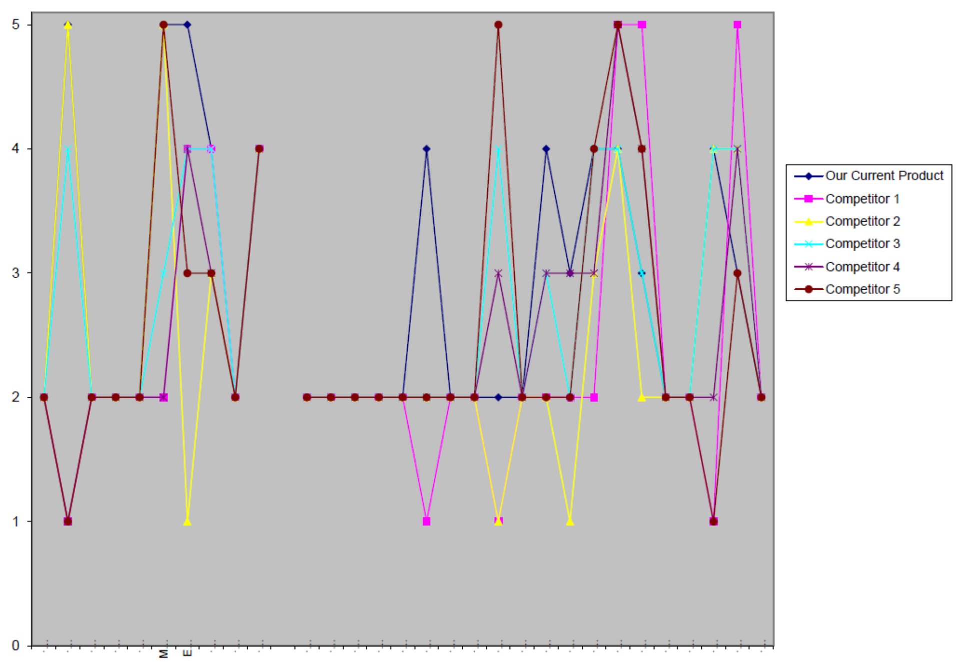


Figure 16. QFD Competitive Analysis for the Product

After selecting the best concept for the space, the course of the design was continued by adding details to it based on the next stage of QFD analysis that was depicting all the necessary functional requirements of the space and their importance. An initial prototype was designed in order to get closer to the final solution, and in order to be able to image all the negative and positive effects of the details that are being added to the model. By showing this prototype to experts the purpose of this project could be better explained and it was possible to get them to think about better alternative ways of achieving the same results or to ask them to suggest even more customer requirements that they would think is necessary. So, the list of customer requirements could be narrowed down and edited based on expert opinions. Also, having a prototype in hand could help us ask for detailed information about the best possible ways of achieving a certain functional performance from the different experts from a variety of disciplines that are involved in the project.

A MCAD software called PTC Creo Parametric was used for designing the prototypes, which is mainly used by product designers. It has good tools for modelling moving mechanisms and checking them with simulations.

In these images the 3D model of the initial prototype is depicted in different states and views:

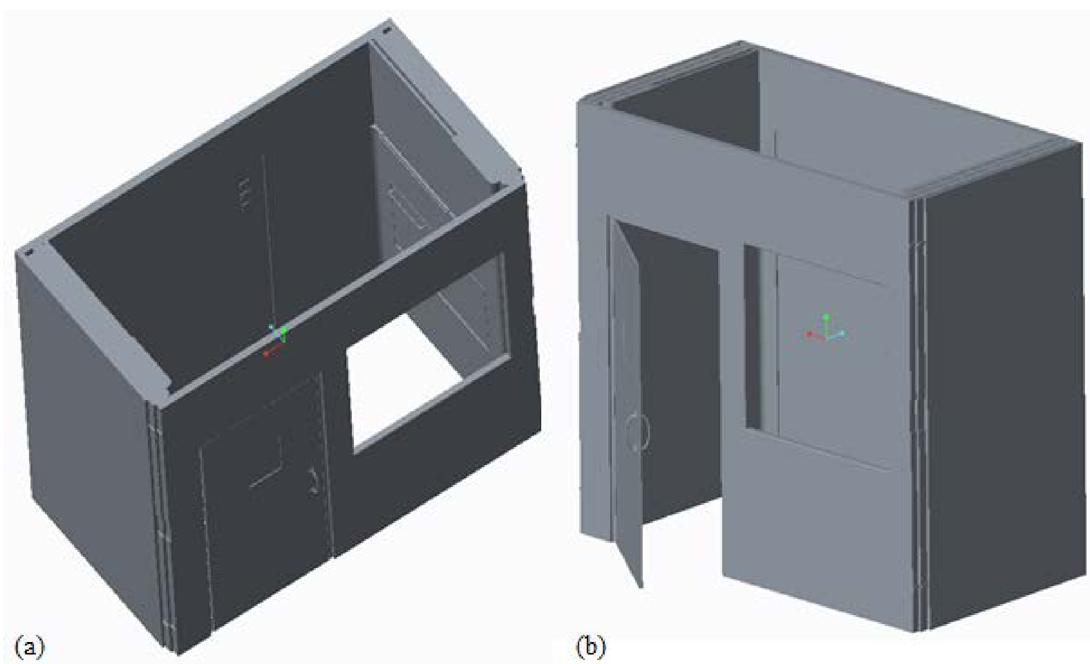


Figure 17. Initial Prototype Model (a) Compacted State Bird's Eye View (b) Compacted State Perspective View

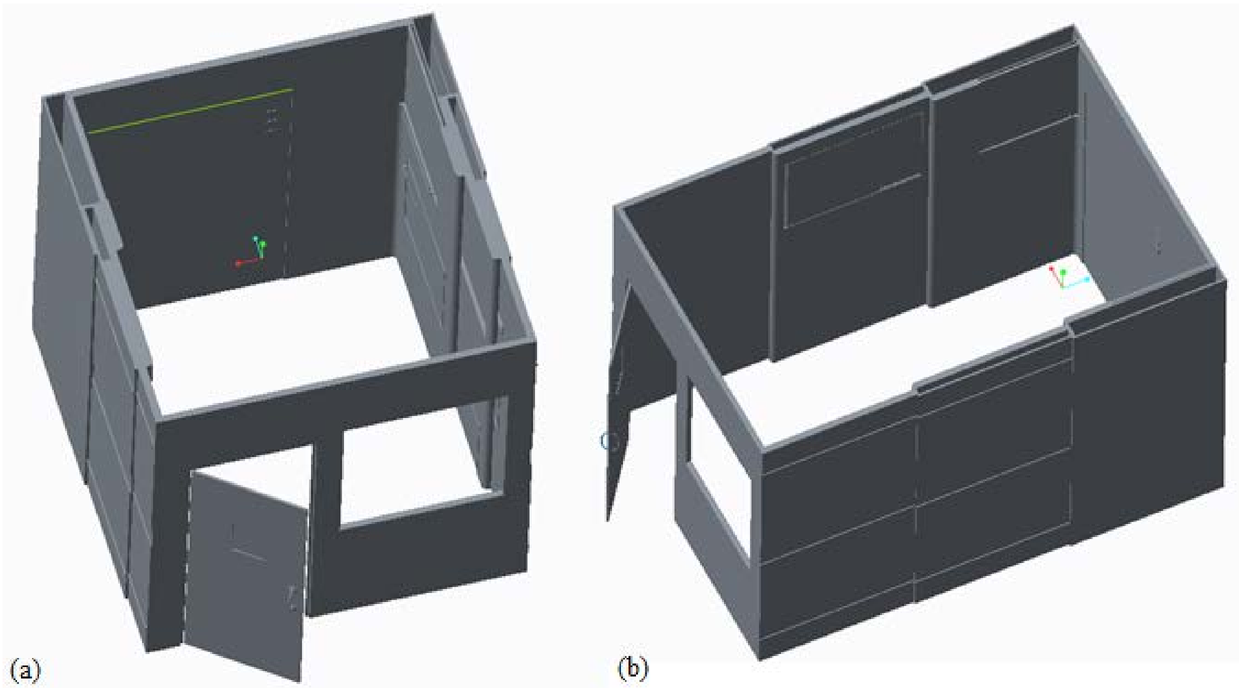


Figure 18. Initial Prototype Model (a) Expanding (b) Expanded Unit and Compacted Furniture

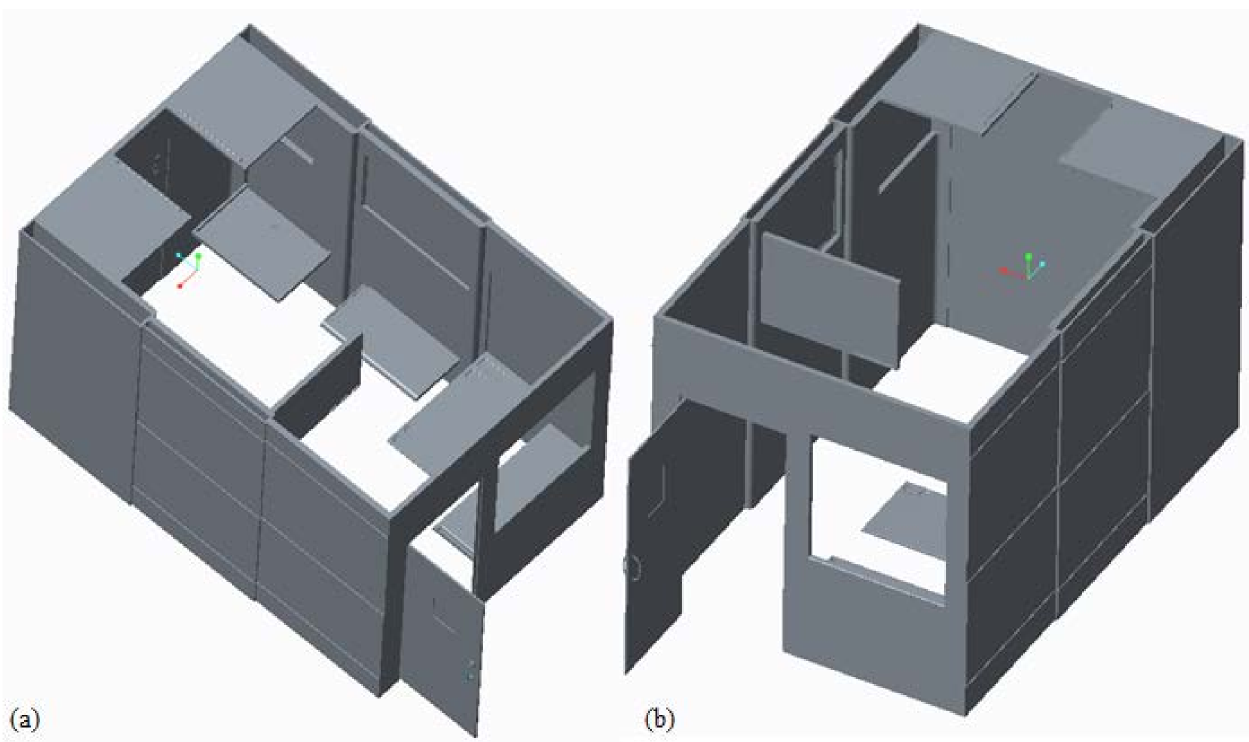


Figure 19. Initial Prototype Model (a) Fully Expanded State Bird's Eye Left Side View (b) Fully Expanded State Bird's Eye Right Side View

All the different parts of the assembly were designed as different modules and they were assembled in the software and checks wre run for the clashes between different parts. Simulations were run of how the different parts should move and rotate and how the whole solution will expand and contract. The approach in the design is parametric which allows for faster and easier changes in the later phases of the design since all the geometrical properties and dimensions are parameters. Simulations make sure that the mechanisms and the moving parts of the solution are designed properly and will work as intended after manufacturing. It is also possible to export a STL file out of the assembly and send it to 3D printers for direct manufacturing of prototype and also the final product. In this design, the needed furniture inside the unit are in the same manner designed in a modular way so that they can be replaced with other alternatives. Because of scale limitations of direct digital manufacturing technologies, it is recommended to design in a modular way so that these smaller modules can be manufactured directly and can be assembled later. One challenge, however, that still remains is that if the proposed materials for the above concept are different then the DDM technologies may not be able to perform multi material manufacturing. In fact, the need for separate assembly process still remains.

Another method that was used to demonstrate the scale of the designed modules and unit was making a prototype out of paper and everyday office use materials. In this way, one can check for the scale issues of the design. However, the level of detail in making this prototype was quite low which could not clearly show the mechanisms and connections. In these photos, you can see the paper made prototype of pre-assembled modules and the assembled unit:

Figure 20. Manually Made Initial Prototype (a) Pre-assembled Modules (b) Assembled Unit

Using 3D Modelling, CAD and Animation and Graphics Design Software for Conceptual Design

MCAD modelling tools were utilized for detailing the prototype and photo-realistic renderings and visualizations and animations were created with 3D modelling software to help to depict what was in mind as a solution in an effective way, so that the customers can feel like they are in the space and they can relate themselves with the prototype helping us to improve it. So, a variety of visualization models were made and the results were shown to experts. Below you can find a set of rendered images using Autodesk Maya software and Mental Ray rendering engine:

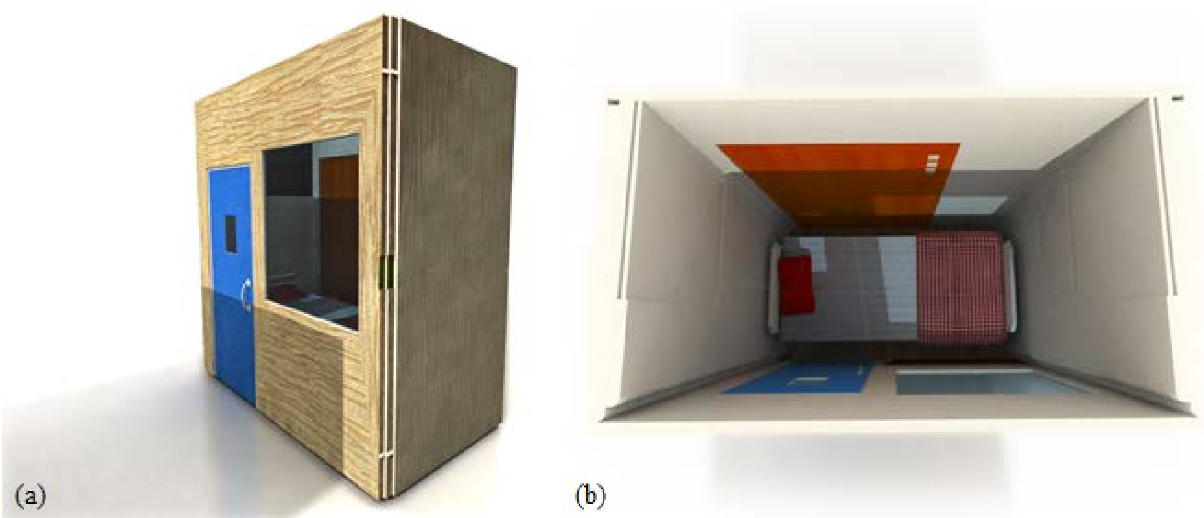


Figure 21. Rendered Images (a) Compacted State Perspective (b) Compacted State Top View

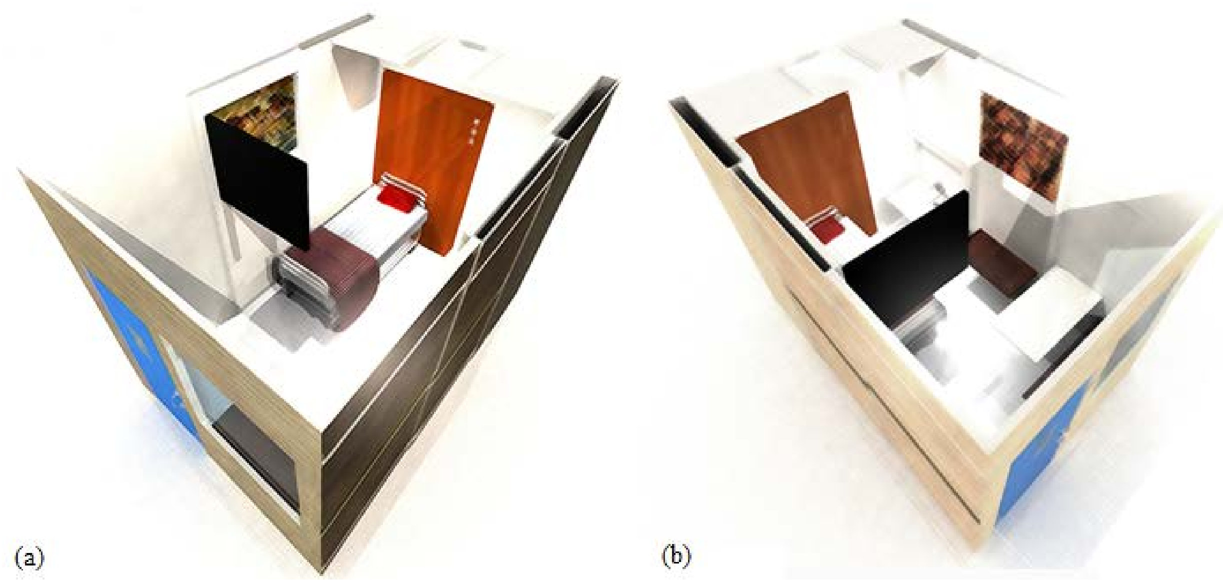
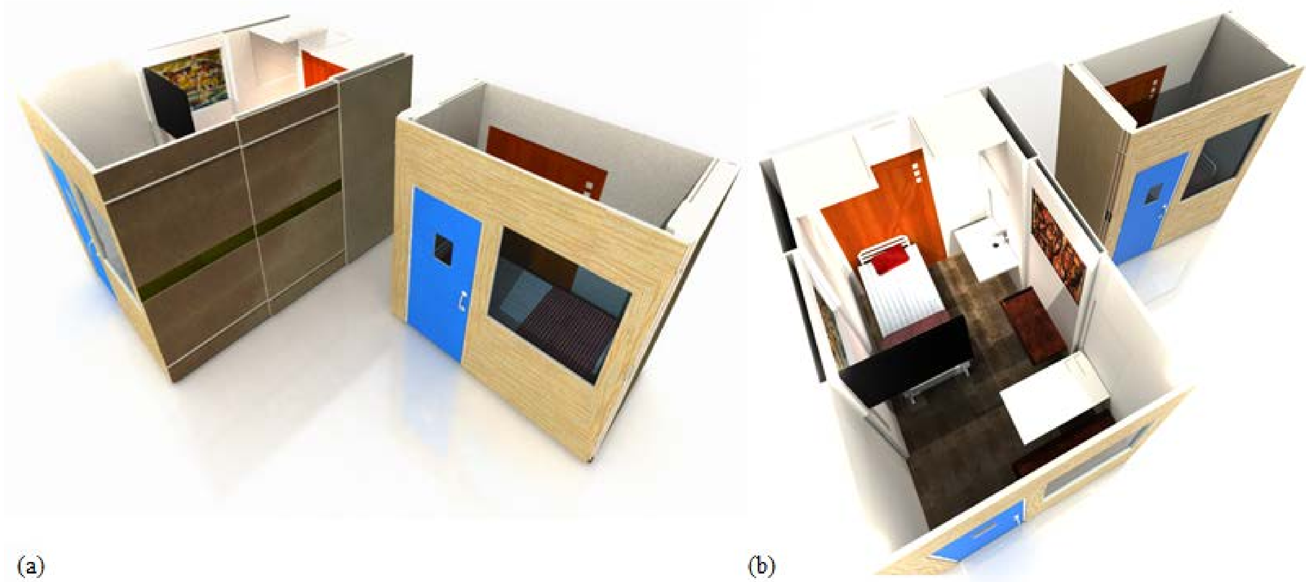


Figure 22. Rendered Images (a) Fully Expanded Unit Bird's Eye Right Side View (b) Fully Expanded Unit Bird's Eye Left Side View



(a) (b)

Figure 23. Rendered Image (a) Expanded and Compacted States Size Comparison Right Side Perspective View (b) Expanded and Compacted States Size Comparison Left Side Perspective View

(a) (b)

Figure 24. Rendered Images (a) Fully Expanded State Bird's Eye View (b) Fully Expanded State Perspective View

Figure 25. Rendered Image, Inside Unit Patient's View

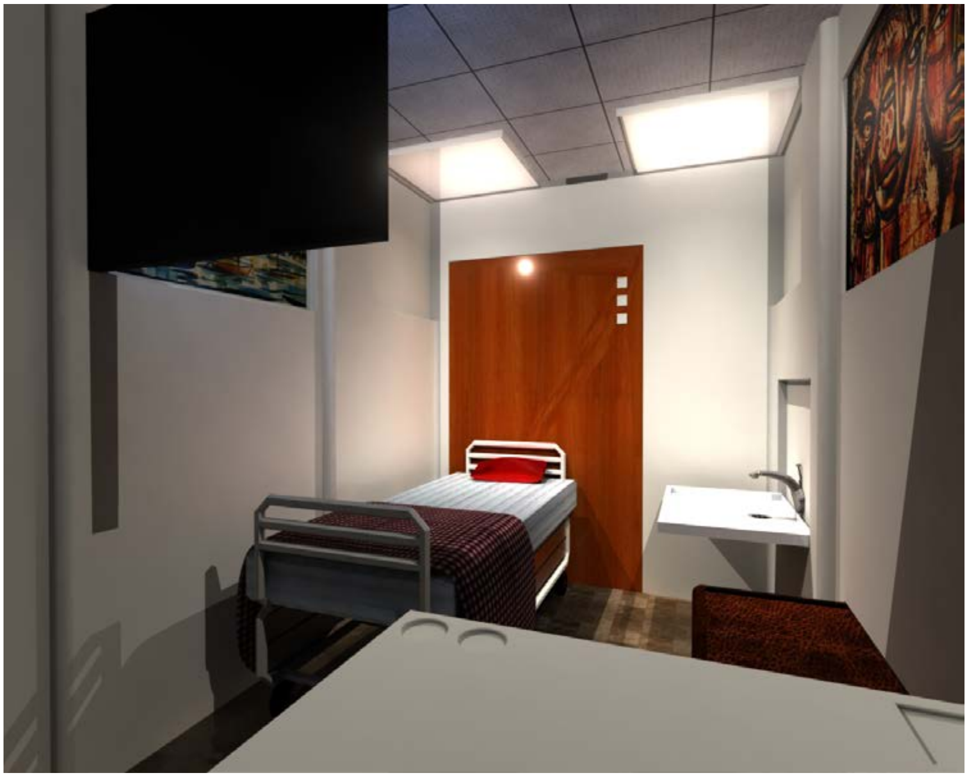


Figure 26. Rendered Image, Inside Unit Visitor's View

Applications of 3D-Printing for Conceptual Deign

As discussed previously, one of the greatest technologies in hand nowadays for rapid prototyping is 3D-Printing as it allows to create a hands-on experience for a prototype of your structure before it is made. It is quite cheap to create models with this technology and the level of complexity of the structure can be infinite, allowing the designer to come up with every possible geometrical solutions that he/she desires with the highest level of detail. However, the biggest challenge in using 3D-Printing for rapid prototyping of structures in construction industry in the scale of the model. The scale is limited depending on the 3D-Printing device that is being used. Using smaller devices to generate a reasonable scale model was a failure and it was needed to switch to a better device. Thus, the biggest scale 3D printer that was available at Aalto Digital Design laboratory (ADDLab) called Gigabot was used which can print models up to 60 cm in height, width and depth.

Here is a photo of some of the parts of the prototype that were created by 3D-Printing:

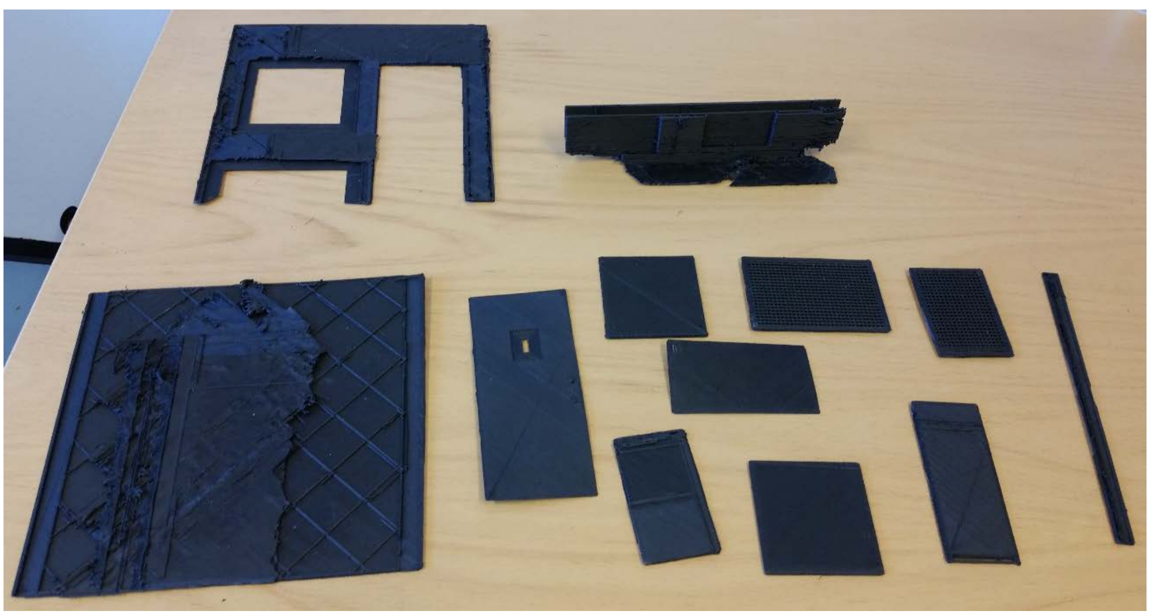


Figure 27. Some of the 3D Printed Parts of the Prototype

Application of Virtual Reality Technology in Conceptual Design

Another tool that was used for conveying the design intentions to experts and end users was Virtual Reality (VR). The VR technology that was used in this project was Google Cardboard which has made virtual reality achievable in a cheap and easy manner through the development of SDKs for Android and Unity Software. Using Google Cardboard SDK one can easily develop games and apps for android devices and the Cardboard itself can be purchased at a very low price or can be manually made out of lenses and papers or plastics (Google, 2016). The 3D model was exported to the Unity game engine and a mobile app was developed that simulates the situation that the end user is inside the designed unit and looking around to get a real sense of how it feels like to be inside the designed unit.

Figure 28. Virtual Reality Glasses Used in This Thesis (a) Google Cardboard Classic VR Glass (b) Spectra Optics Industries VR Glass

It is possible to introduce animations and user interactions with the designed objects inside this virtual world. Thus, VR can have great potentials to be used by architects to convey their design intentions and to design with a better perspective and a better sense, since it allows them to sense the feeling of living and interacting with built environment before it is built. This platform can also be used as a learning environment where users can virtually travel around the world and learn about different features of a building on their screens. It is quite straightforward to develop a 2D interface which depicts different types of information along with the 3D interface. In the construction industry, combining photogrammetry and VR can lead to the technologies which allows engineers and workers on site to visualize what they are constructing in its correct position before construction which can reduce errors drastically. Facility managers can utilize the VR technology to virtually walk inside facilities and check for defects and fix them online. All in all, this new technology can have many useful applications in the areas of design, construction and management of built environment.

In this thesis, I developed apps that create a virtual hands on experience of interacting with the designed unit and seeing how it expands and how it performs as realistic as possible with the current available technologies. However, as of today VR is being rapidly developed and many other devices by other companies have been released namely HTC Vive, Oculus Rift, Sony PlayStation VR, Samsung Gear VR, Microsoft HoloLens, Razer OSVR, FOVE VR, Zeiss VR One, Avegant Glyph, Freefly VR headset, etc. that create a virtual reality experience. Some of these devices work with PCs and some with smartphones, some make it possible to create an augmented reality experience which combines the virtual images with the real views, some have sensors detecting the movements of the person wearing them, and some have special joysticks to give more controls to the player. The competition in developing such devices is too fierce and it is probable that by the time this thesis is being read many of these technologies are obsolete and replaced by better ones. Below a couple of smartphone screenshots of the developed apps are shown:

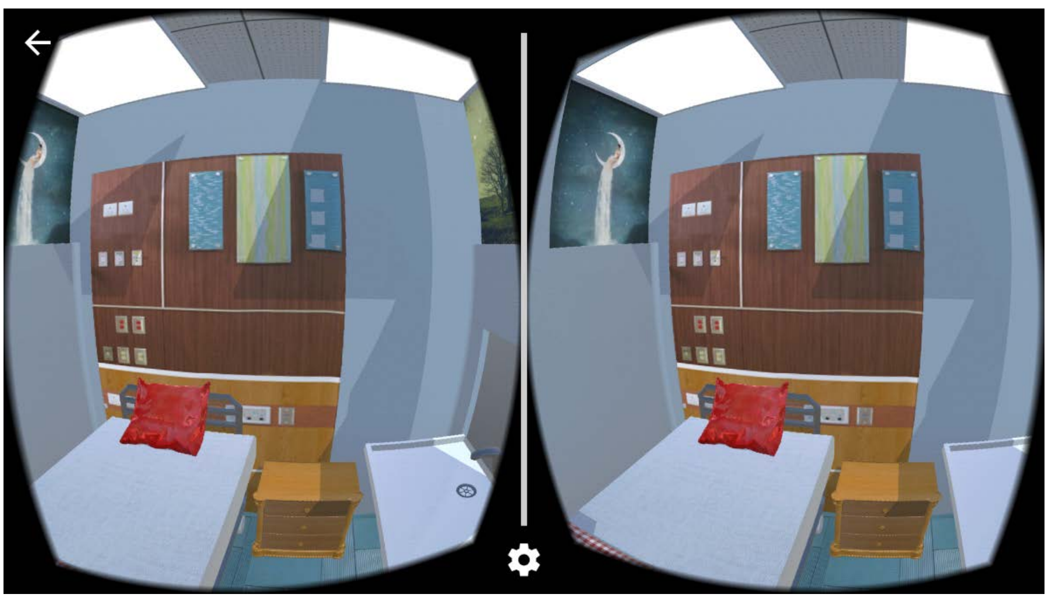


Figure 29. Virtual Reality Model of the Initial Prototype, Back View Screenshot

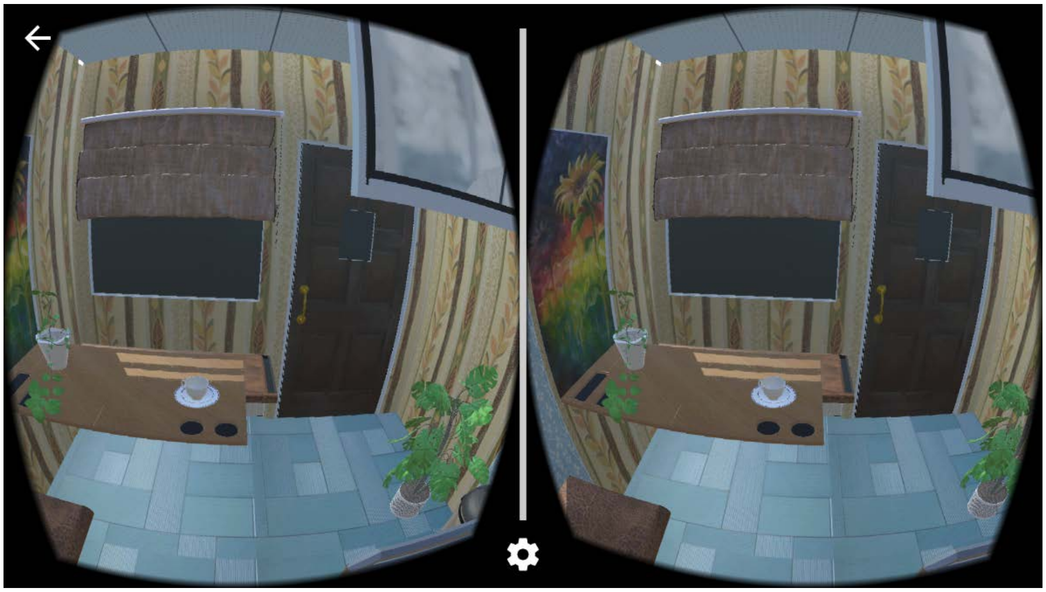


Figure 30. Virtual Reality Model of the Initial Prototype, Back View Screenshot

Developing the Design Based on Expert Opinions

In interviews with experts, efforts were made to find more and more customer requirements and they were also asked to enlighten the way to achieve those requirements in diverse design principles such as design for direct digital manufacturing in interviewing with Ville Pietilä (the educational section of M.A.D. Company) and Professor Jan Holmström (professor at Aalto University Department of Industrial Engineering and Management specializing in Operations Management), construction management perspectives in interviewing with Professor Antti Peltokorpi (professor at Aalto University School of Civil and Structural Engineering specializing in Construction Management), indoor air quality in interviewing with professor Heidi Salonen (professor at Aalto University School of Civil and Structural Engineering specializing in Indoor Environmental Engineering), etc. Here some of the most important key points mentioned by experts to help develop the concept are listed:

- One big challenge in utilizing direct digital manufacturing technologies is that the available technologies do not support multiple materials to be directly manufactured at once, so either the designer must stick to one material or separate parts of the products must be assembled after being manufactured.
- Aesthetics and architectural design of the interior space must be given a high value since it directly affects the comfort and satisfaction of patients.

- Design standards of different disciplines must be all met at the same time which makes the detail design a multidisciplinary project.
- It is worth exploring international challenges that may rise because of differences in controlling systems, standards, cultural differences, authoritative rights, etc. if the units are to be placed in multiple countries while maintaining remote connectivity and controllability.

CHAPTER 4: Methodology Development: Development of the Theoretical Framework

Introduction

So far, a systematic approach has been followed in the design of these modular units. As it was one of the main features of the SPACYPHY units to be collapsible when not needed, one of the challenges was dealing with the furniture that was necessary for each specific use case. Every time the unit expands and compacts, the furniture had to be taken in and out which was not a convenient solution. Instead, foldable furniture were designed for the unit that do not need to be taken out of the unit but they allow the unit to be compacted. In this design approach, one of the main principles that was recommended to be used was structure sharing since many parts of the structure of the unit could be shared with the structures of the furniture.

As the terms and available methodologies for structure sharing and estimation methods for creating optimized design solution were briefly discussed, it was found that the available methodologies do not take into account some factors that were important in this project. So, some new methodologies for the estimation of effectiveness of the structure sharing were developed and the design of the units was analyzed based on the newly developed methodologies as a case study.

Limitations of the Current Models of Structural Sharing

Previous to this research, the quantitative measures that were giving an estimation of the degree of structure sharing and resource effectiveness of the product had some limitations that made these measures not completely reliable for the engineers in their design decisions. Firstly, these models didn't take into account the quality of function. Meaning that the designer is not sure that the sharing of structure is keeping the same quality of the expected function in the product. As a matter of fact, in many cases the designer might be dedicating the quality of functions which can be regarded as the quality of the product to reach higher resource effectiveness. Secondly, another issue with the current measures for the estimation of effectiveness of structure sharing is that they don't consider the negative effects that appear when structures are shared. Sharing of structures can result in the generation of some new unwanted functions and behaviors that will affect the overall satisfaction of the customers (Chakrabarti and Singh, 2007). Some design examples will be reviewed for further explanations. Thirdly, many of the sub-functions and their related behaviors that are generated through structure sharing might remain unused. These sub-functions and behaviors help in achieving other functions, but themselves might have possible other applications that the designer is overlooking in the design. This will reduce the affordance of the design.

In this thesis, methodologies have been developed that attract the attention of the designer towards these issues.

Developing a New Model for Quantitative Analysis for the Structure Sharing Decision Making

Here, a new model is proposed for the analysis of design alternatives in cases that the designer is using structure sharing principles in the design. This new model will take into account multiple issues. The final user is playing a central role in the results of this analysis.

One is the relative importance of the main functions. The preferences of the user are given a high value in the design. So, in cases where the product is providing multiple main functions for the user, his/her importance weight for these main functions are taken into account. The main reason to bring this forward is in many studied cases the designer come up with innovative structure or function sharing ideas, but the users are not very interested in them because they don't see a very important use out of them to pay more for the many other functions that the product is providing. So, it is crucially important for the designers to look into the target market that they are designing the products for and gather their preferences and feedbacks before integrating multiple functions and structures in one single product.

Another factor that is taken into account is the quality of function. As the problem was introduced in the previous section, it is very important to check how well the functions are being performed by the products. Durability, robustness, ease of use, and other measurable aspects that are related to the performance and functioning of the product can be used to determine the quality of different functions in a product. In this method, it is suggested that the designer compares the quality of functions in the shared and unshared cases. In this way he/she can judge how much of the performance is being deteriorated or improved when he/she is sharing the structures to increase resource effectiveness. The judgment can be done by using the measurable performance related and durability related parameters (like speed, tensile or compressive strength, pressure capacity, flow rate. etc. depending on the design case).

Likewise previous models for estimations of structure sharing it is yearned to reduce the total number of structures that are used in the design and increase the simplicity of the design. So, it is suggested to the designers to compare the total number of structures in the shared and unshared cases to see how much they are reducing the amount of materials and resources that are used. In this methodology, the emphasize is on the fact that the reduction of physical parts will not necessarily result in reduction of costs and resource effectiveness because it might impose technical difficulties in the manufacturing process and unwanted costs may rise and this makes the save in the material consumption not worthwhile in the overall production process and life cycle of the product.

Furthermore, the negative effects that are generated in an unintentional manner during the course of the design are accounted for. These effects can be negative behaviors that will be unfavorable for the end user. There are many design cases that the end users prefer to have multiple functions at the same time in one product, however, structure sharing will impose limitations for them. In such cases, the designer can conduct an analysis to see if the structure sharing is imposing new limitations and can check to see whether these disadvantages are acceptable or not.

The New Methodology: Checking the Admissibility of the Design

In the presented methodology, the beginning step is identifying all the structures and main functions and sub-functions and behaviors of a product. So, at first a FM-tree is drawn for all the separate main functions of the product (the method for drawing an FM-tree was previously discussed in this thesis). Next, all the customer requirements and engineering requirements are gathered and a QFD matrix is formed with them. And, now that a proper understanding of the structures that are involved in that particular design alternative is reached and the requirements of the customer are clarified the designer can calculate the value of a term that is called as “Admissibility of Sharing” and is calculated using the Eq. (4) below:

$$Adm = \frac{\left(\Sigma RI \cdot RQOF \cdot \frac{1}{S} \cdot \frac{1}{1+NNE}\right)}{\left(\Sigma RI \cdot \frac{1}{S} \cdot \frac{1}{1+NNE}\right)} \tag{4}$$

In the above formula, the terms are as follows:

RI: Relative Importance of Main Function

RQOF: Relative Quality of Function

S (In the nominator): total number of structures in the structure shared solution

S (In the denominator): total number of structures in the unshared solutions

NNE (In the nominator): total number of negative effects for the structure shared case

NNE (In the denominator): total number of negative effects for the unshared case

Now, let us briefly discuss the methodology that is being proposed to the designers to derive the numerical values for the above terms.

Relative Importance: Relative Importance of each main-function shows the degree which it is effective in the final performance of the product and the degree that it can result in customer satisfaction. A relative importance value can be assigned to each of the main-functions by giving an importance rating from 1 to 5 to each. As a more reliable approach to obtain the relative importance of each main function, the QFD customer requirements analysis can be used and the ratings of experts and regular customers of the target market can be gathered and by giving weight to the values given by experts a weighted-average for the value of importance can be derived.

Relative Quality of Function: It is a value between 0 and 1 that the designer can allocate to a shared solution by assuming that the unshared solution has full quality of function (=1). Quality of function can depend on multiple factors. RQOF can be numerically determined based on functional requirements of the design, derived from QFD Analysis or other methods in which the designer can measure how well a functional requirement is being satisfied.

As one method for deriving RQOF from numerical analysis instead of qualitative design thinking, the functional requirements analysis in QFD can be used. In this method, a target value or a minimum numerical value for different design characteristics is being set and these properties in the solutions can be measured and it can be seen how close they are to the target and whether they pass the minimum requirements or not. By summing over all the functional requirements the overall performance of shared and unshared solutions can be numerically compared.

Number of Negative Effects: By counting the negative effects that are the result of sharing or not sharing the number of undesirable effects that each case (shared/unshared) is imposing on the environment of the product can be determined. It can have multiple forms like wasting space, clashing with other elements or products, affordance of the design, ease of use, mobility of the product, solution not being multi-purpose or any other negative effects that the designer can identify in the context of the solution and its surrounding environment.

It can also be determined based on customer requirements in the QFD Analysis, by taking into account the relationships between all of the customer requirements and functional requirements and their negative inter-relations.

Negative effects of each individual main function can be thought of and also negative effects of sharing on the overall solution can be considered. Those overall negative effects will be considered in all the main functions, however, each main function is imposing its own negative effects. As another suggested method for deriving the number of negative effects, the QFD analysis can be utilized. By looking at all the customer requirements the design team can see if they are satisfying each or not. If not, then that is a negative effect.

Number of Structures: the number of structures can be counted from the end points of the branches of the FM tree or by asking the design software to count all the structures that are involved in the shared/unshared solutions.

During this thesis, a plugin was developed to be working inside the BIM software, Autodesk Revit, and it allows the designer to select the objects and count the number of structures and it then calculated the admissibility of sharing based on the entered values for other terms.

One important aspect that needs to be considered when counting the number of structures, is to check whether there are operations that need to be done on one single physical entity to make it a useful part. For example, cuts and holes and bends are needed in the manufacturing process to turn a solid piece of geometry into one part of an assembly. These operations also incur costs and must be counted as a separate structure. For instance, if there are 3 manufacturing processes to be done on 1 part, that 1 part is counted as 3 in the above formula. As a matter of fact, the designer must try to reduce the complexity of the design to make it more efficient and only reducing the amount of consumed material is not sufficient to make the whole design and manufacturing more efficient and resource effective.

Admissibility of Sharing: This value is calculated by Eq. (4), by summing over all the sub-functions. On the nominator each term corresponds to shared solution and in the denominator each term corresponds to unshared solution.

A value over 1.0 shows that the sharing is admissible and the bigger the value, the more logical is the design decision. A value below 1.0 tells the designer that not sharing the structure is more beneficial as it will result in customer dissatisfaction from the performance of the product.

Example Case: How to Apply the New Methodology

Now let us have a brief look at a couple of examples for the analysis with this methodology. Let us consider the design of an innovative product that is combining the functionalities of a pen and that of a USB:

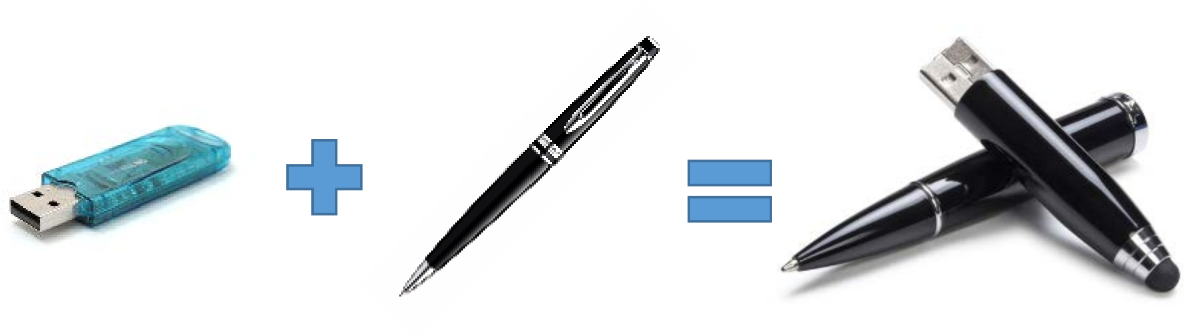


Figure 31. Example Design Case - Multipurpose Pen

By conducting an Admissibility of Sharing analysis the designer can check whether this is going to be a successful product or not. As explained, the first step is to construct FM trees of the products, one for each of the unshared products and one for the shared concept that has been developed. The higher the level of detail in the FM tree, the more reliable will be the results of the analysis. It is important to note that the FM trees that were used for the purpose of developing the methodology were not necessarily very accurate and complete, rather they were simplified so that they could be understood in a short time for the purpose of conducting the workshops and experiments. However, in real design cases constructing a very accurate FM tree is crucial in achieving reliable results. Below you can see the mentioned FM trees constructed:

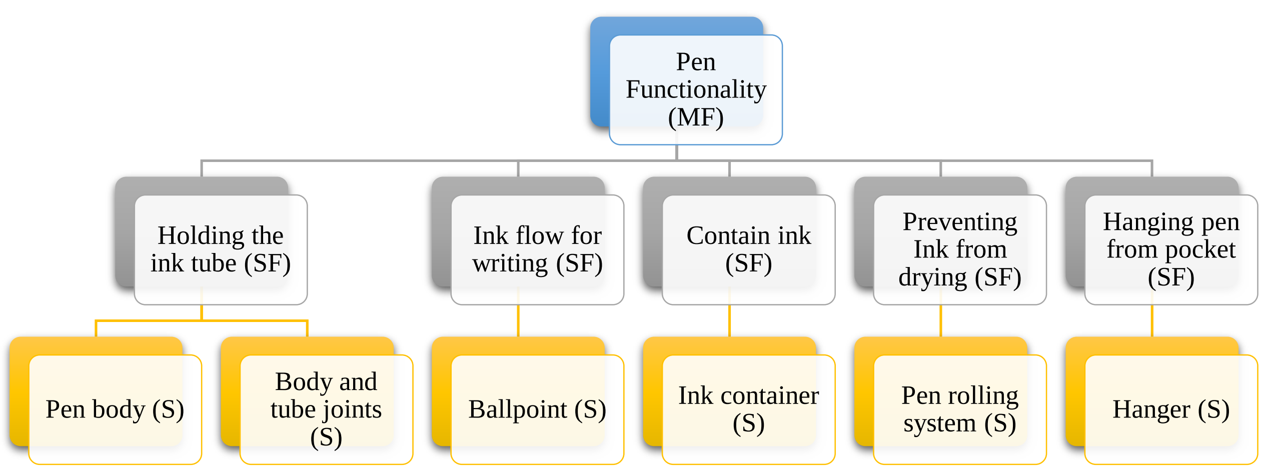


Figure 32. FM Tree of a Typical Pen

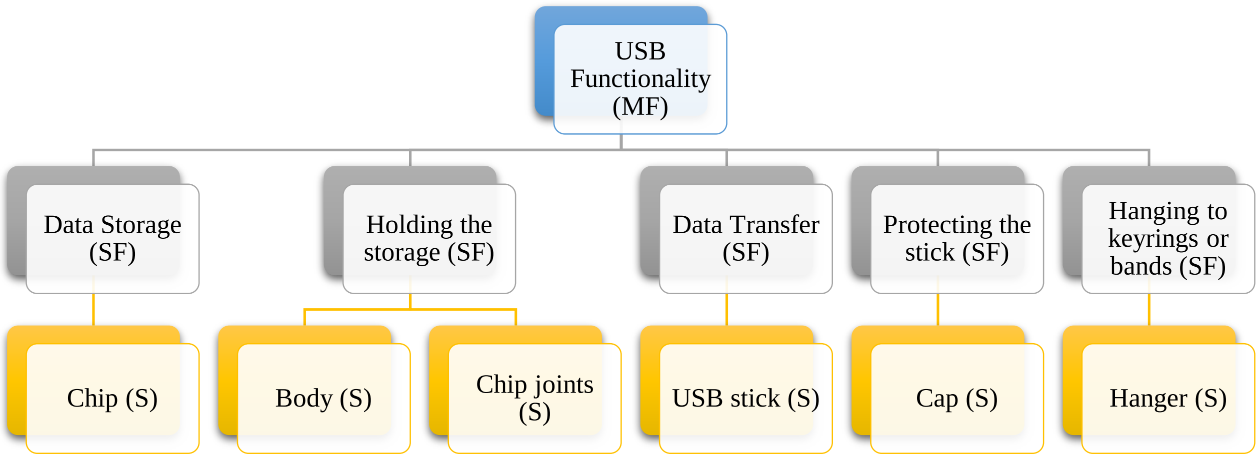


Figure 33. FM Tree of a Typical USB Memory Stick

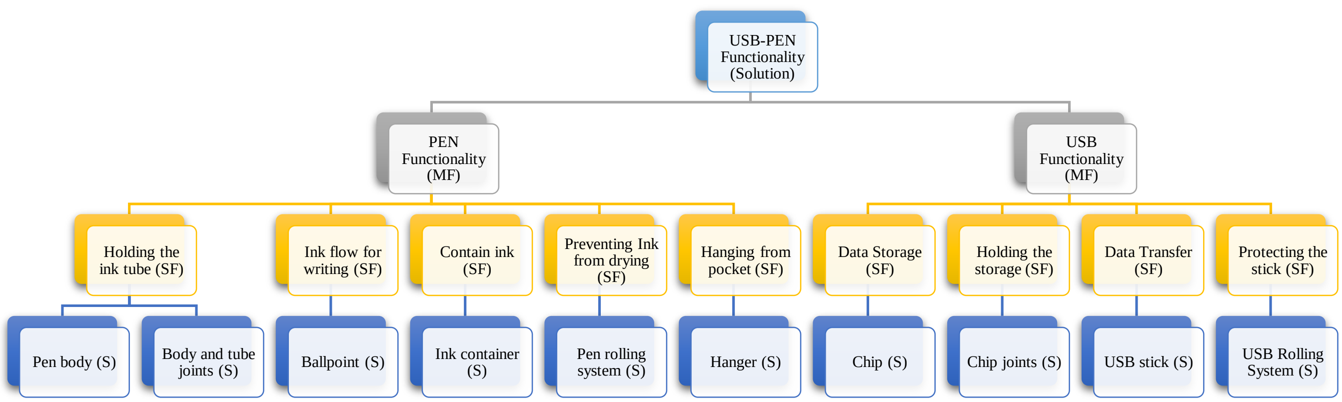


Figure 34. FM Tree of the Designed Solution (USB+Pen)

These FM trees help to identify all of the main functions that will be performed by the product and also they help to recognize the exact number of structures that are involved in the solution concept and in each of the typical unshared solutions. Another alternative approach would be selecting all the structures in the model inside the plugin that has been developed inside the CAD or BIM design software and in this way the number of structures are accurately estimated. Figure 35 shows the user interface of the developed plugin:

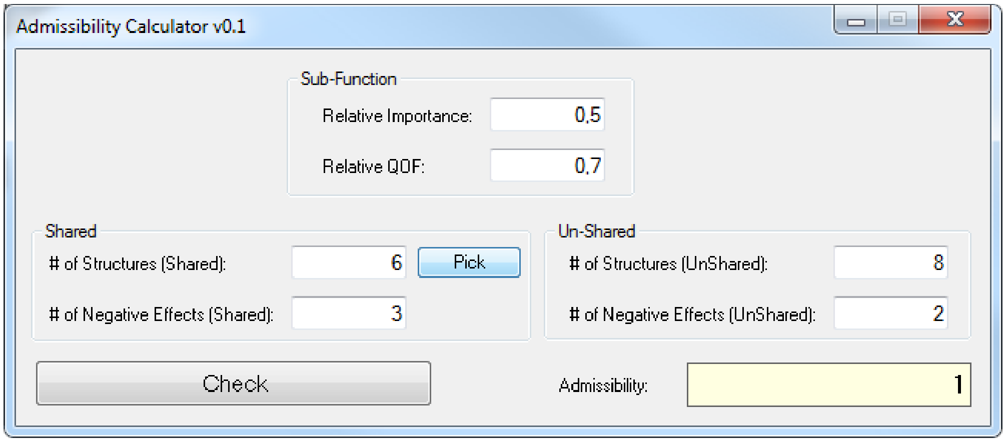


Figure 35. User Interface of the Computational Software

The next step is to determine the relative importance of each of the main functions for the end user. To assign a meaningful number to the RI values individual designers and customers are asked to give a value of importance from 1 to 5 to each of the main functions (here being the functioning as a pen and functioning as a USB memory stick) and subsequently, by calculating an average value of their importance rating more reliable values can be allocated to these fields. So, in average a value of 0.62 is derived for the relative importance of pen function and a value of 0.38 for the relative importance of USB function.

The next step is to estimate the relative quality of each of the main functions. In other words, to estimate how well the pen in this solution is performing in comparison to a normal typical pen, and how well the product is functioning in comparison to a single USB memory stick. The designer can freely allocate qualitative values of what he thinks is the quality of function between 0 and 1. However, as a more reliable approach it is best to rely on the QFD analysis of the product to gain more accurate results. So, the method that is suggested to derive the value of quality of function is by looking at the engineering comparisons made between the target values of the engineering requirements and their measured values in the design. In this example case, it can be noticed that because of the limitations on the length of pen and the amount that it is being shortened because of the placement of the USB memory stick the ink storage has to be shortened, so the amount of ink stored will be reduced. So, by dividing the amount of ink in the solution by the amount of ink in a normal typical pen (which is the target value) a number between 0 and 1 is calculated. This process can be repeated for all the other engineering requirements in the solution. QFD chart gives the value of importance of the engineering requirements by relating them to the customer requirements and the importance of customer requirements. After all, deriving a weighted average over all of the engineering requirements while the weight factor is the importance of the engineering requirement can produce the most accurate and reliable value for the relative quality of the main functions. Below, you can see the analysis example in this design case:

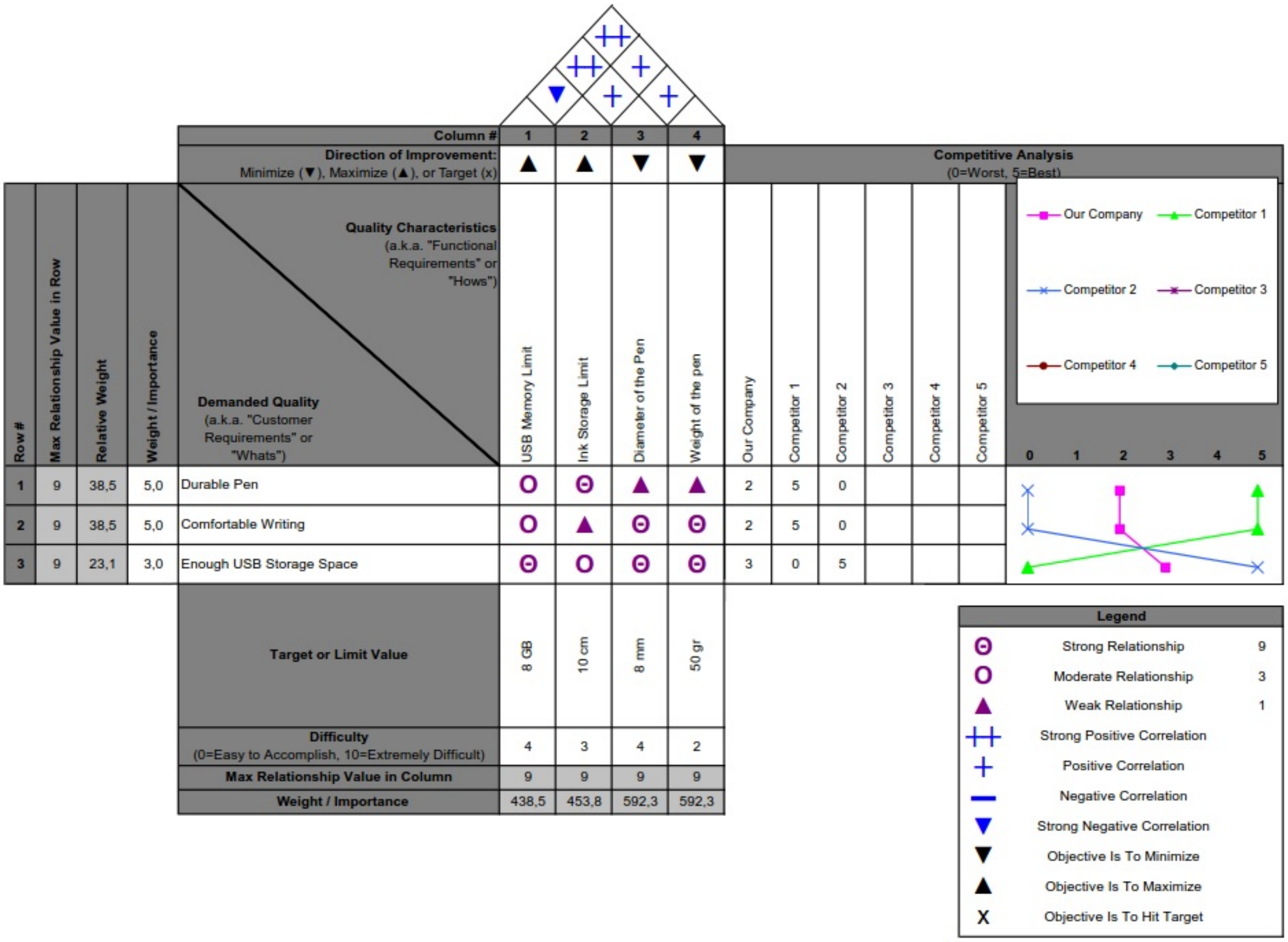


Figure 36. QFD Analysis of the USB-PEN

In the above QFD chart it is assumed that an unshared normal pen to be Competitor 1 and an unshared normal USB memory stick to be the Competitor 2, and in this way a qualitative rating for the position of the concept compared to unshared solution can be given. Thus, this can be a more qualitative approach in deriving the quality of main functions. In here, the value of quality of function is derived numerically by taking into account the target (or limit) values and the weight/importance of functional requirements, as follows:

Measured USB memory limit: 4 GB

Target value for USB memory limit: 8 GB

Measured ink storage limit: 6 cm

Target value for the ink storage limit: 10 cm

Measured value for the diameter of pen: 12 mm

Limit value for the diameter of pen: 8 mm

Measured weight: 70 gr

Target weight: 50 gr

$$Relative\ QOF\ of\ pen\ function = \frac{454}{454+593+593} \times \frac{6cm}{10cm} + \frac{593}{454+593+593} \times \frac{8mm}{12mm} + \frac{593}{454+593+593} \times \frac{50gr}{70gr} = 0.66$$

So according to the analysis the pen in this solution is having 66 percent of the performance of a single pen. Similarly, for the USB function:

$$Relative\ QOF\ of\ USB\ function = \frac{439}{439} \times \frac{4GB}{8GB} = 0.5$$

So the solution is half good as a single USB memory stick.

There is one more step to take to be able to calculate overall admissibility of sharing and that is to identify the negative effects. By looking into each individual customer requirement the different types of interactions of the end user with the product can be identified and a list of all the negative types of behaviors that this structure sharing is creating for the users can be created. These negative effects are more or less context dependent and it is important to know what exactly will be the environments where users are interacting with the product and what are the other products that might be interacting with the product. In this example case, these negative effects can be considered to exist for the unshared and shared scenarios:

Negative effects of using unshared pen:

- You need to carry it separately in case you need it

Negative effects of using unshared USB memory stick

- You need to carry it separately in case you need it
- It is more probable that you lose it somewhere

Negative effects of using the shared solution:

- It is not comfortable while writing
- Can’t use both pen and USB at the same time
- When the ink runs out half of the performance is gone and the structure is useless

So, we have 3 (=2+1) total number of negative effects of using the unshared solutions, and 3 total number of negative effects of using the shared solution.

Lastly, the value of admissibility of sharing can be derived by the given formula manually or by using an excel spread sheet:

$$Adm = \frac{\left(\Sigma RI \cdot RQOF \cdot \frac{1}{S(shared)} \cdot \frac{1}{1+NNE(shared)}\right)}{\left(\Sigma RI \cdot \frac{1}{S(unshared)} \cdot \frac{1}{1+NNE(unshared)}\right)} \tag{5}$$

MFs	IR	RI	RQOF	S(U)	S(S)	NNE(U)	NNE(S)				
Functions	Importance rate (1-5)	Relative Importance	Relative Quality of Function (Shared)	Number of Structures Serving for Each Function (Unshared)	Number of Structures Serving for Each Function (Shared)	Number of Negative Effects (Unshared)	Number of Negative Effects (Shared)				
PEN	4,71	0,62	0,66	6	6	1	3	0,01705	0,05166667		
USB	3	0,38	0,5	6	4	2	3	0,011875	0,02111111		
	7,71							0,028925	0,07277778	Admissibility	0,397443

Figure 37. Sample Excel Sheet for Calculation of Admissibility Value

And finally, a value of 0.39 has been estimated for the admissibility of sharing.

Analysis of the result: as the result is a number below 1, it shows that in the perspective of end users this will not become a successful product even though it is more resource effective and might be cheaper than buying the two products of single pen and single USB memory stick.

In the cases that there are multiple design concepts in mind, this methodology can help to pick the best option by giving the end user a central role in the process of the design.

Validation of the New Methodology

To validate if the proposed methodology and model will work fine and is applicable in the different fields of engineering design, different methods were used.

First, a set of different designed products were analyzed to check if the methodology is understandable and applicable. Then, a set of guidelines was composed to explain the methodology to other researchers and designers to check if the methodology can be understood by different designers. Additionally, they were asked to do the analysis of the same products that were analyzed before to see how subject dependent would be the results, and to check if the model is giving consistent results. Then, after that the methodology itself and its guidelines were finalized, its results were checked by analyzing two sets of products. One set that seemed to be successful products in a marketing point of view and according to customer satisfaction ratings. And another set of unsuccessful products that had utilized the structure sharing techniques but had failed to gain customer satisfaction and good sales in the market. In this phase, it was intended to check if the formula is giving reliable results in predicting the success of a product. In the next phase, the methodology was explained and the guidelines were handed out to a group of master's level students of structural design and architectural design and they were asked to do the calculations and determine if the methodology is helpful in giving them a perspective for the design. In addition, with this method it was possible to check if the results of the previous analysis conducted by myself can be reliable and are not biased towards getting a specific result.

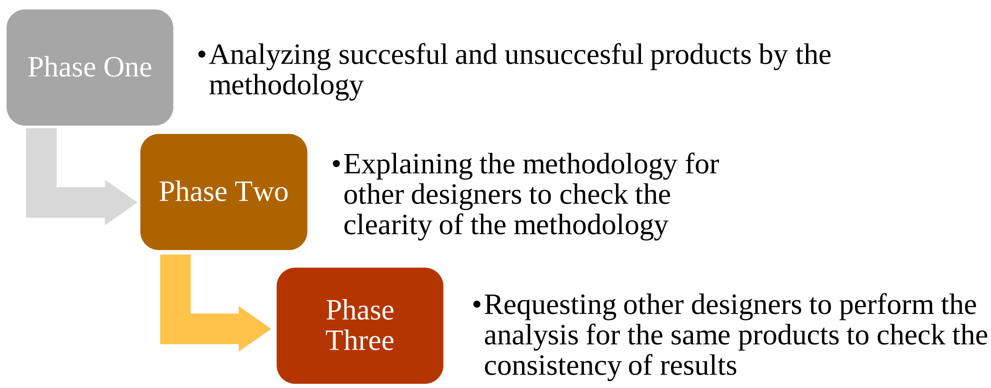


Figure 38. Methodology Validation Experiments Flowchart

Here are the results of the experiments to validate the methodology:

Phase one: in this phase, a list of products were analyzed with the methodology and checked whether the predictions of the methodology for the success of the product align with the market success of the products. Below you can see the admissibility values calculated for the chosen products.

Table 5. Results of the Analysis for Some Successful and Unsuccessful Products

Successful Products	***Admissibility Value***
Smartphone	2.97
Passenger Seat	4.12
Unsuccessful Products	
USB-PEN	0.39
Laptop-Table	0,65

Phase two: in this phase the methodology was explained for a group of researchers and they were asked to perform the analysis for some example cases and their opinion about the clarity of the guidelines and their suggestions for the improvement of the methodology were asked. Results of the workshop was as follows:

- Other researchers believed that the methodology was straightforward to understand, but a bit time consuming to do the calculations by hand and on paper.
- They pointed out that there must be more clear definition of structure in the guidelines
- Their FM trees for the same products had some differences that could result in different answers
- Overall, it was possible for them to learn and apply the methodology in less than 2 hours
- After the workshop, a brainstorming meeting was conducted with other researchers to ask for their ideas to improve the methodology further and to find more applications for it.

Phase three: in this phase a group of master's degree students of structural and architectural engineering were requested to perform the analysis for the two given products. The main outcomes are as follows:

- Almost all of the students had at least two years of work experience in design related tasks.
- They found the methodology easy to learn and to apply in less than 2 hours for two products.
- They were given FM trees and a basic QFD sheet and were asked to complete it if they thought it was necessary. They were asked to add or remove any items that they thought was necessary from the FM trees and QFD matrices before running the analysis.
- They had to fill in a table containing all the parameters that are needed for calculating the admissibility value, and later the value of admissibility of sharing could be calculated with an excel spread sheet.
- They were also asked to write down their thoughts and especially the list of negative effects that they were thinking about.
- Their analysis was done individually for the two selected products and below you can see the results:

Product Case 1: The same design of the USB-Pen

Results of the admissibility calculations of individual students and the average admissibility value:

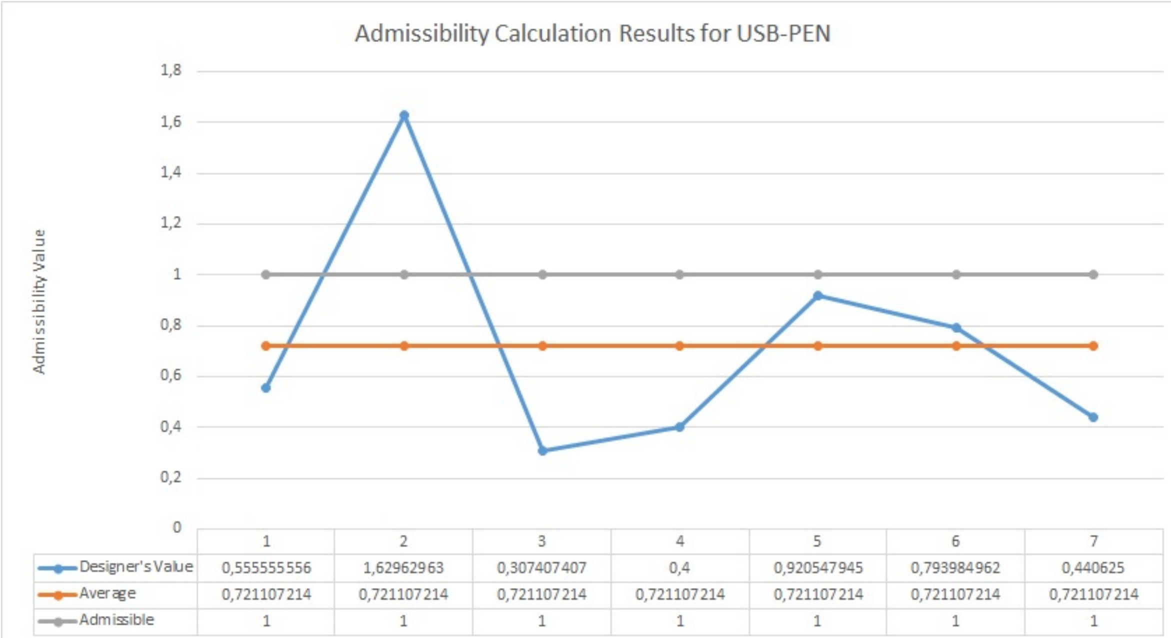


Figure 39. Results of Analysis in the Workshop (USB-PEN)

Product Case 2: The design of smartphones that combine mobile phone functionalities with camera functionalities. The derived admissibility value by myself was 2.97 which indicates a very good design.

Results of the admissibility calculations of individual students and the average admissibility value:

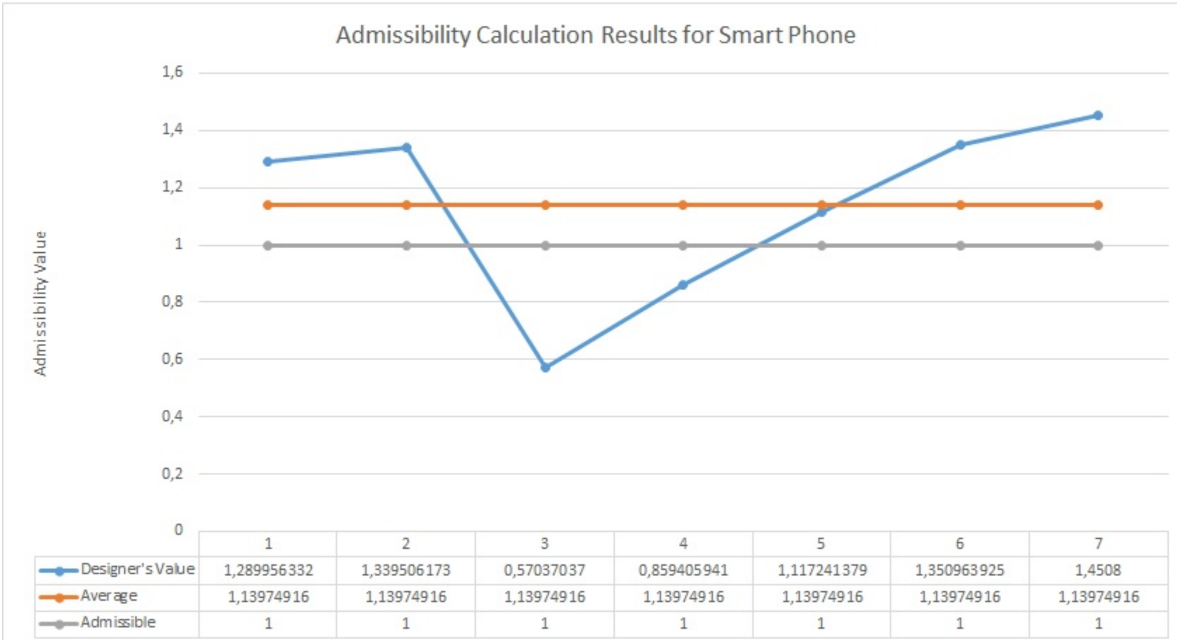


Figure 40. Results of Analysis in the Workshop (Smartphone)

Analysis of the Results of the Experiments:

For the first case, it can be noticed that 6 out of 7 students derived a value below 1 which is similar to my own derived value and shows that the design will not be successful, and 1 student derived a value over 1 showing that it will be a satisfactory design. The average value of admissibility is below 1 which can stand for the final conclusion of the design team that this innovative idea may not be worth developing any further.

In the second design case, it is observed that 5 out of 7 students derived a value over 1, and 2 students derived a value below 1. Again, the mid value and the average value are over 1 and similar to my own finding it shows that it is a very good innovation. However, it is worth noting that the result of the analysis is up to a point subjective and it is always good to rely on the opinions of more people to get closer to a definite value. Drawing of FM trees and identification of negative effects can differ based on the concept, context and the designer's caution. So, one suggestion to achieve more reliable results is to use polls, surveys, and batches of analysis in the design groups so that statistics can compensate the probabilistic differences and can lead to a better answer.

Refining the Methodology for Further Applications and Improvements

Simplifications for Quick Practical Use

In the course of developing this methodology it was found that the guidelines can be a bit hard to grasp for everyone and it was needed to make some simplifications to the methodology so that it can be understood and can be applicable within a reasonable amount of time. And, it was in this case that the methodology could be scaled up to the vast number of cases to be analyzed in a construction project, for instance. So, as for some simplifications that can be made to proceed faster with the methodology, the designer can personally identify the main functions that he/she is designing the product for and can count the number of structures from his/her design software and for the negative effects he/she can place himself/herself in the role of customer and see what are the limitations that this structure shared solution has imposed on the customer and for the values of relative importance he/she can assume that all of the main functions have the same weight of importance for the customer. These simplifications make the analysis much faster but at the same time they reduce the level of accuracy and reliability of the results of the analysis.

Usability in Different Stages of Design

It is worth noting that it is important to define the phases of the design that applications of this methodology is viable. It is clear that the introduced methodology is not a design tool but it is rather an analysis tool. There should be first one or multiple concepts in hand and then one can reengineer the design by this type of analysis and then the design and analysis can be repeated multiple times to refine the design solution. However, one may ask if the methodology is as well applicable in the early stages of conceptual design phase where there is no solution at hand. In that stage, the designer can begin with using the most typical and conventional engineering solutions that exist and quickly develop a preliminary concept and then by applying the structure sharing techniques he/she can improve the concept and come up with more innovative solutions.

Using the Methodology for Increasing the Affordance of the Structure Shared Products

The applications of ‘Theory of Affordance’ in design has created a toolset to establish connections between the purpose of the design with how the product will actually be used (Maier and Fadel, 2001, 2002). Affordance of a product shows the ability of the user to use a product for a purpose other than the main purpose that it has been designed for. The higher the affordance of a product, the more innovative it will be and the more convenient it will make the life for the user. For instance, a smart phone as a product has a high affordance since it allows every user to add to its functionalities through the development of apps and programs that can perform many functions other than the main functions of the mobile phone.

When looking at the FM trees of the structure shared products it can be seen that many of the structures that are serving to achieve the specific functions or sub-functions in each product component are having multiple behaviors and only some of those behaviors are being used to achieve the required functions while other behaviors are left unused in the design. These unused behaviors can be considered a type of waste since there are always many ways to perform the same function and other ways can be selected that have less unused behaviors. Many of these unused behaviors are negative behaviors while many can have positive uses and can lead to helpful features for the users if they are thought of in the design phase and if the needed actions are taken by the designer. In other words, in the process of design the designer must identify all the unused behaviors and then he/she can decide whether those can serve to achieve other functions that can be helpful for the end user. For instance, the body structure of a pen has a weight that can be thought of as a positive behavior for holding the papers on the table in a windy day. Or the ink of the pen can be used to draw electrical circuits if it has conductive substance. However, the individual unused behaviors of different structures might not be enough to perform additional functions and they must be integrated together and some additional structures might be needed to establish the new added features. For instance, in the case of holding the papers by pen no additional structure is needed, but in the case of drawing electrical circuit conductive substance as additional structure should be added to the ink which will incur costs. Again, the same question here rises that this thesis has been trying to answer which asks whether the user is willing to pay more for those additional structures or not and whether they are user's demands and how important are they for the user.

The designer can use the same presented methodology to check if these additional functions are worth designing for. First, an FM tree is constructed of the concept that the designer has in mind and in this way all the needed functions and sub-functions are identified. Next, the designer looks into all the structures that are serving to fulfil these functions. The behaviors of all of the structures are identified and the ones that are remaining unused are marked.

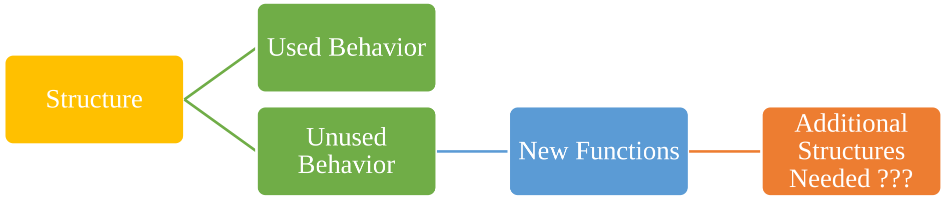


Figure 41. Analysis Approach Steps in the Presented Methodology

At this stage, creative design thinking methods such as TRIZ can help the designer find other uses for these unused behaviors. While associating other uses to the same structures, it is important to check if additional structures are needed or not. If so, another FM tree is constructed with the additional structures and added functions. Now, the presented methodology can be utilized to see if this design is favoring the end user and is increasing resource effectiveness in total or not. Once more the tables for the added functions and their quality and relative importance for the end user and the negative effects that are generated by the newly added structures can be filled. The same formula is applied here as well:

$$Adm = \frac{\left(\Sigma RI \cdot RQOF \cdot \frac{1}{S(added)} \cdot \frac{1}{1+NNE(added)}\right)}{\left(\Sigma RI \cdot \frac{1}{S(initial)} \cdot \frac{1}{1+NNE(initial)}\right)} \tag{6}$$

If the result of the analysis shows that the admissibility of the sharing has increased after adding the new structures and functions, then it is a better design and if the value of admissibility has decreased the new design is rejected. It is worth noting that the new structures that have been added will have other unused behaviors. So, the same approach can be repeated to add more and more functions and features for the end user while maintaining the least number of structures and the highest degree of resource effectiveness that leads to lower price in general. This methodology increases the affordability of the final product because the end user will be able to use the product for many other purposes than the main functions that the product provides.

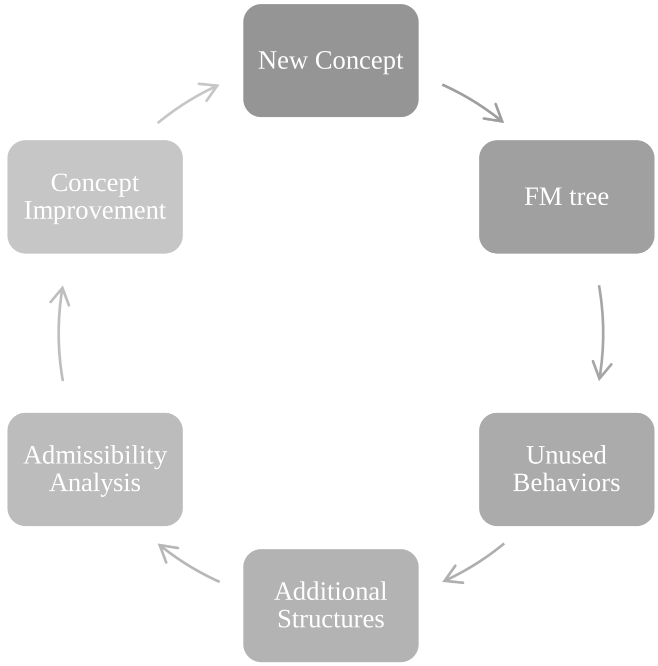


Figure 42. Design Approach Using the Presented Methodology

Design Example Case: Ruler Pen

Here is one example of how a designer can increase the affordance of the designed product by using the presented methodology. The goal is to analyze the design of a pen and to try to increase its affordance for the end user.

Figure 43. Example Design Case (Ruler+Pen)

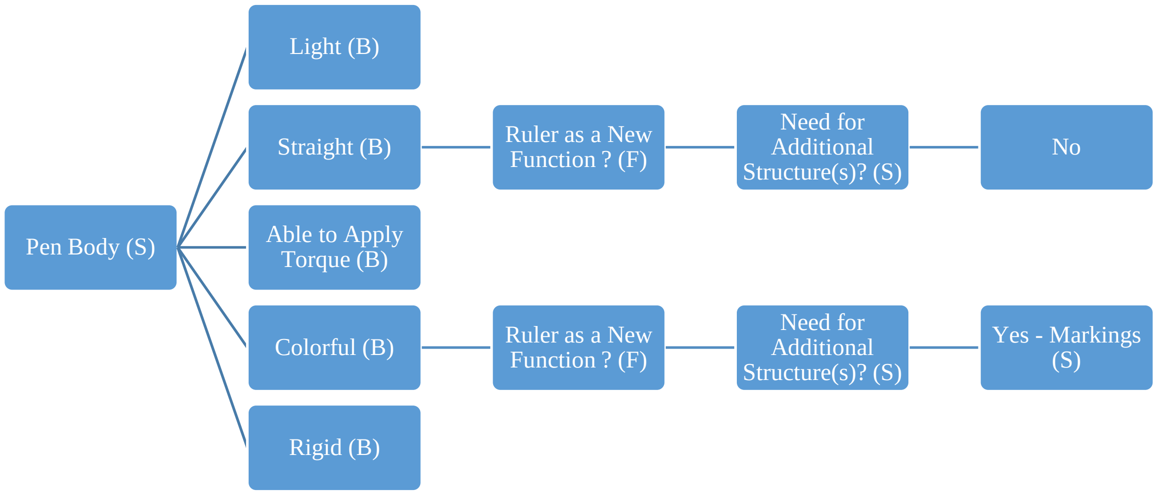


Figure 44. Partial FM Tree of the Pen with Behavior Identification

By looking at the FM tree of a typical pen some behaviors of the different structures used in the design can be identified that can be utilized to achieve other purposes. For example, the body of the pen is straight and colorful and if ruler markings (as an additional structure) is used it is possible to achieve the ruler function, as well. Here, depending on the target market and the needs of the users a set of admissibility analysis can be run to see if the additional function (ruler) is needed by the end users and if they are willing to pay for the additional structures that the designer needs to use in the design to achieve that function.

Admissibility Analysis:

Admissibility of pen before adding the ruler function: 1.036

MFs	IR	RI	RQOF	S(U)	S(S)	NNE(U)	NNE(S)				
Functions	Importance rate (1-5)	Relative Importance	Relative Quality of Function (Shared)	Number of Structures Serving for Each Function (Unshared)	Number of Structures Serving for Each Function (Shared)	Number of Negative Effects (Unshared)	Number of Negative Effects (Shared)				
PEN	5	0,625	1	3	3	1	0	0,208333333	0,10416667		
Eraser	3	0,375	0,5	1	2	1	0	0,09375	0,1875		
	8							0,302083333	0,29166667	Admissibility	1,035714

Admissibility of pen after adding the ruler function: 1.465

$$Adm = \frac{\left(\Sigma RI \cdot RQOF \cdot \frac{1}{S} \cdot \frac{1}{1+NNE}\right)}{\left(\Sigma RI \cdot \frac{1}{S} \cdot \frac{1}{1+NNE}\right)}$$

MFs	IR	RI	RQOF	S(U)	S(S)	NNE(U)	NNE(S)				
Functions	Importance rate (1-5)	Relative Importance	Relative Quality of Function (Shared)	Number of Structures Serving for Each Function (Unshared)	Number of Structures Serving for Each Function (Shared)	Number of Negative Effects (Unshared)	Number of Negative Effects (Shared)				
PEN	5	0,454545455	1	3	3	1	0	0,151515152	0,07575758		
Eraser	3	0,272727273	0,5	1	2	1	0	0,068181818	0,13636364		
Ruler	3	0,272727273	0,7	2	1	1	0	0,190909091	0,06818182		
	11							0,410606061	0,28030303	Admissibility	1,464865

So by adding the ruler function to the existing design, the admissibility of structure sharing is increased in favor of the end user. In this way, the affordability of the pen has been increased since it will be used for another purpose than its main purpose. There are still some behaviors of the structures in this design (applying torque for example) that have remained unused and can be further thought of to increase the functionalities and affordance even further.

Here, it is worth noting that designing a set of experiments to validate the use of the presented methodology to increase the affordance of a product and conducting the experiments was beyond the scope of this master's thesis and it will be a part of the future work.

CHAPTER 5: Conclusions and Further Work

In this chapter, we present some discussion and further work on the developed methodologies and we summarize how the designed concept is analyzed using the developed methodologies. We will also mention the possible other use cases for the designed product and we introduce the new research opportunities for further work in this topic.

Discussion and Further Work on the Engineering Design Methodologies

One question still remains regarding the quantitative measure of admissibility which is the fact that one may ask if the linear relationship between all the terms of the function can give the best answer. As a matter of fact, in the presented model the effect of all the terms (number of structures, number of negative effects, etc.) is equally strong. However, it might be necessary to give more weight to one term over the others. In other words, it will be a very good practice to calibrate the model to derive the values of α, β, γ and δ coefficients in the following general version of the model in Eq. (7):

$$Adm = \frac{\Sigma\left(RI^{\alpha} \cdot RQOF^{\beta} \cdot \left(\frac{1}{S(shared)}\right)^{\gamma} \cdot \left(\frac{1}{1+NNE(shared)}\right)^{\delta}\right)}{\Sigma\left(RI^{\alpha} \cdot \left(\frac{1}{S(unshared)}\right)^{\gamma} \cdot \left(\frac{1}{1+NNE(unshared)}\right)^{\delta}\right)} \tag{7}$$

The coefficients used in these studies are:

$$\alpha = 1 \tag{8}$$

$$\beta = 1 \tag{9}$$

$$\gamma = 1 \tag{10}$$

$$\delta = 1 \tag{11}$$

By following experimental methods, one can look into a wide variety of products in different markets analyzed by a wide variety of designers and then it will be possible to calibrate the model based on those results to make it more reliable in predictions. However, since a sufficient amount of results are not yet available it is not very feasible to proceed further in this area in this thesis.

Utilizing the Computational Design Techniques and the Newly Developed Methodology

The presented design solutions were analyzed by the analysis methods that were described in the background section and also this conceptual design project was used as a case study for the methodology that was developed for assessing the effectiveness of structure sharing. In this design, there are plenty of the cases of structure sharing because in this concept it was required to deal with the foldable furniture so that the units can expand and compact without the need to relocate furniture inside. The developed methodology were applied in the design of these furniture to check if it will be a logical decision in each case. In the table below you can find the results of the calculations of admissibility value for all the different cases of structure sharing.

Table 6. Summary of the Results of Admissibility Calculations for the Initial Concept of SPACYPHY Units

Item	Admissibility of Sharing	Design Confirmation
Headlight	1,486	OK
Sink	1,269	OK
Headwall	1,243	OK
TV Place	1,355	OK
Picture Frame	1,063	OK
Nurse Seat	0,773	Not Good
Visitor Seat	0,769	Not Good
Visitor Table	1,059	OK

In all cases, in the concept, some part of the structure of furniture is being shared with the walls. The shown values are derived based on the intuitions of the designer about the quality of function in each case and the negative effects and behaviors that he could find in the context of the specific use case of the units for health care environment. Since, the requirements of health care facilities are very intricate and strict the allocated values of relative quality of function might not be very reliable and further research is needed to derive more realistic values. Also, depending on the particular use case of the unit for different needs namely patient rooms, special care rooms, elderly care rooms, etc. the number of negative effects might vary which leads to different results. For instance, based on the preliminary analysis results it can be noticed that visitor seat and nurse seat in the designed concept have not received a high admissibility value which indicated that this design might not be the best solution available. The designed seats are not very comfortable and robust and they can’t be moved which is a significantly negative behavior. Other parts of the designed concept seem to be ok.

Other Use Cases and Applications of the Concept

There might be multiple other use cases for the designed unit since it is parametrically designed and can be customized easily for other use cases. The unit can be extended in size and then be used as a semi-private space or a double room for patients who prefer to avoid staying alone in single patient rooms. The unit can serve as a visiting room for doctors who can be a part of a satellite hospital having the possibility to move their visiting pod to the cities and areas where aid is urgently needed. Similarly, the unit can be customized to provide a space for other health care activities such as first aid units, surgery rooms, ICU units, waiting rooms, laboratories, X-Ray rooms, etc. The requirements of the design in each case is different and has to be studied carefully before changing the design. Also, as the unit is movable it can be used as a blood collection pod in the streets.

Nevertheless, apart from the use cases in the health care environments, the designed unit can be customized for a variety of other use cases. It can be used as a movable storage space that can be placed outside the buildings and can be compacted when not needed. Another use case would be automatic make-ready classrooms that are booked by professors to be active for a certain time and after the class ends the unit shrinks down for the save of space and energy. It also can be used as a bookable meeting pod providing meeting space for people in many locations across the country. Satellite hotels can be formed to provide accommodation services nationwide and especially when there is an urgent need for accommodation namely in festivals, exhibitions, sports competitions, etc. The designed pod can create a private room inside the buildings which makes it useful for people who need to have an added room in their apartments. The units can also be used for exhibition and advertising purposed around the city and variety of other services such as fast-food kiosks, ice-cream kiosks, movable saunas, etc. The unit can be used as a tourist unit when fastened to a car for camping and touring. The unit can be specifically customized to create a laboratory or studio atmosphere for people to work at home or work distantly for instance the people who need dark rooms, acoustic rooms, UV treatment rooms, heat treatment rooms, etc.

Once again, it is worth pointing out that all of these mentioned use cases need to be studied for their customer requirements and engineering requirements and then the alterations in the design can be feasible. With the presented methodology it is clear now how to gather and organize the requirements, how to make the design decisions, and how to present it to end users and experts for improving the design. Thus, one can use the same design methodology for designing units for all the other use cases.

Research Limitations

During this thesis work, there were some limitations faced that could hinder the process of research and design, and the intention for mentioning them is to prevent them in the later research. The biggest limitation for research in this area was time. As a matter of fact, the limited time allocated to M.Sc. thesis was not sufficient to develop the idea up to the full size prototyping and piloting and test marketing stages. So, it is hoped that the course of research and design continues. Secondly, as it can be seen the opinions of end users and experts play a critical role in the presented approach, making it a limiting factor in the speed of research and design. In fact, there were times it was needed to wait for a long time until an expert could answer back to the inquiries. Solutions to accelerate the process of gathering the opinions include using online surveys and conducting more workshops and brainstorming sessions which, however, was beyond the scope of this thesis. After all, another limitation was the financing of the project that limits the number of team members and hinders the prototyping and piloting process. It is hoped that the introduced concept gains enough attention from investors so that the process of research and design continues.

Further Research Opportunities

There still remain lots of challenges and questions in the areas of design and research. The concept can initiate the process of detail design which is an interdisciplinary project introducing new design and research opportunities for architects, structural engineers, mechanical engineers, HVAC designers, software developers, industrial engineers, health care experts, etc. to continue the design of the physical space according to the needs of customers and to carefully design the manufacturing process and to develop the needed software infrastructure to connect and control all the units.

In addition, in the area of engineering design this research is opening new doors to bring in more and more methodologies into design thinking process and to automate the process of design. The area of affordance of the design can be studied further and the presented methodologies can be tested and optimized even further.

Conclusion

In this thesis, we initiated a new concept for the design of healthcare facilities. The applications of product development techniques in the design of the modular distant units were investigated and it was shown that there are many useful methodologies mainly used in other design fields that can be used in the design of structures and built environments, too. A product is developed that can alleviate many problems relating to the existing healthcare facilities and can improve the quality of care received by patients and the elderly. An idea of distributed connected units that can form a new ecosystem of facilities to provide satellite services was explored. Conceptual design and presentation techniques were explored and the potential advantages and disadvantages of using DDM technologies in structural and built environment design were discussed. New methodologies in engineering design were proposed and their helpfulness was validated. Finally, new opportunities for the design for other use cases and further research opportunities were put forward.

References

Akao, Y. (1997) QFD: Past, Present, and Future. In: *International Symposium on QFD '97*. [online] Available at: http://www.qfdi.org/QFD_History.pdf [Accessed 10 Oct. 2015].

Amick, B. C., Robertson, M. M., DeRango, K., Palacios, N., Allie, P., Rooney, T., and Bazzani, L. (2002). *An Overview of a Longitudinal Quasi-Experimental Field Study to Evaluate the Effect of An Office Ergonomics Training and a New Chair on Quality of Work Life, Health, and Productivity*. Proceedings of the 6th International Scientific Conference on Work with Display Units. Berchtesgaden, Germany: Ergonomic Institut fur Arbeitund Sozialforschung Forschungsgesellschaft.

Amick, B. C., Robertson, M. M., DeRango, K., Bazzani, L., Moore, A., Rooney, T., and Harrist, R. (2003). Effects of an Office Ergonomic Intervention on Musculoskeletal Symptoms. SPINE 28 (24): pp. 2706 – 2711.

Ampt, A., Harris, P., and Maxwell, M. (2008). *The Health Impacts of the Design of Hospital Facilities on Patient Recovery and Wellbeing, and Staff Wellbeing: A Review of the Literature*. Liverpool, NSW, Australia: Centre for Primary Health Care and Equity, 92.

Anderson, R. L., Mackel, D. C., Stoler, B. S. and Mallison, G. (1982). Carpeting in Hospitals: An Epidemiological Evaluation. *Journal of Clinical Microbiology* 15 (3): pp. 408 – 415.

Andreasen, M. M. and McAloone, T.C. (2008) *Applications of the Theory of Technical Systems –Experience from the "Copenhagen School"*. Plisen: AEDS Workshop [online] Available at: http://orbit.dtu.dk/fedora/objects/orbit:54268/datastreams/file_3342041/content [Accessed 20 Nov. 2015].

ASHRAE (1995). *Chapter 48. Noise and Vibration Control*. In: ASHRAE Handbook. Heating, Ventilating and Air-Conditioning Applications, edited by B. Parson. Atlanta, GA: American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE), Inc.

Balocco, C., and Lio, P. (2010). Modelling Infection Spreading Control in a Hospital Isolation Room. *Journal of Biomedical Science and Engineering* 3 (7): pp. 653 – 663.

Bartley, J. M., Olmsted, R. N., and Haas, J. (2010). Current Views of Healthcare Design and Construction: Practical Implications for Safer, Cleaner Environments. *American Journal of Infection Control* 38 (5 Suppl. 1): S1 – S12.

Bassoli, E., Gatta, A. (2007) 3D printing technique applied to rapid casting. *Rapid Prototyping Journal*. Turin: Emerald Group pp.148-155. [online] Available at: http://www.emeraldinsight.com/loi/rpj [Accessed 10 Feb. 2016].

Bayo, M. V., Garcia, A. M., and Garcia, A. (1995). *Noise Levels in an Urban Hospital and Workers' Subjective Responses*. Archives of Environmental Health 50 (3): pp. 247 – 251.

Ben-Abraham, R., Keller, N., Szold, O., Vardi, A., Weinberg, M., Barzilay, Z., et al. (2002). Do isolation rooms reduce the rate of nosocomial infections in pediatric intensive care units? In: *Journal of Critical Care*, 17(3), pp. 176-180.

Beyea, S. C. (2007). Noise: A Distraction, Interruption, and Safety Hazard. *AORN Journal* 86 (2): pp. 281 – 285. [online] Available at: http://findarticles.com/p/articles/mi_m0FSL/is_2_86/ai_n27348328 [Accessed April 10, 2012].

Beyer, D. J., and Belsito, D. V. (2000). *Fungal Contamination of Outpatient Examination Rooms: Is Your Office Safe?* Dermatology Nursing 12 (1): pp. 51 – 53.

Biley, F. C. (1994). *Effects of Noise in Hospitals*. British Journal of Community Nursing 3 (3): pp. 110 – 113.

Boyce, J. M., and Pittet, D. (2002). Guideline for Hand Hygiene in Healthcare Settings – Recommendations of the Healthcare Infection Control Practices Advisory Committee and the HICPAC/SHEA/APIC/IDSA Hand Hygiene Task Force. *American Journal of Infection Control* 30 (8): 1 – 46.

Bioquell (2015), Bioquell Pod [online] Available at: http://www.bioquell.com/en-us [Accessed 8 Jan, 2016].

Cardboard (2016), Google Cardboard [online] Available at: https://www.google.com/get/cardboard [Accessed 20 Apr, 2016].

Carling, P. C., and Bartley, J. M. (2010). Evaluating Hygienic Cleaning in Health Care Settings: What You Do Not Know Can Harm Your Patients. *American Journal of Infection Control* 38 (5 Suppl. 1): pp. 41 – 50.

Carpman, J. R., and Grant, M. A. (1993). *Design That Cares: Planning Health Facilities for Patients and Visitors*. 2nd ed. Chicago, IL: American Hospital Publishing.

Carr, R. F. (2011). *Hospital*. In: Whole Building Design Guide. Vol. 2011, Revised by the WBDG Health Care Subcommittee. Washington, DC: National Institute of Building Sciences. [online] Available at: http://www.wbdg.org/design/hospital.php [Accessed August 1, 2012].

CDC (2003). *Guidelines for environmental infection control in health-care facilities.* Morbidity and Mortality Weekly Report, 52 (RR-10).

CDC and HICPAC (2003). *Guidelines for Environmental Infection Control in Healthcare Facilities: Recommendations of CDC and HICPAC.* Atlanta, GA: Centers for Disease Control (CDC) and Prevention and Healthcare Infection Control Practices Advisory Committee (HICPAC), pp. 71 – 88.

CDC and HICPAC (2007). *Guideline for Isolation Precautions: Preventing Transmission of Infectious Agents in Healthcare Settings*. Atlanta, GA: Centers for Disease Control and Prevention (CDC) and Healthcare Infection Control Practices Advisory (HICPAC).

Chadhury, H., Mahmood, A. and Valente, M. (2004) *The Use of Single Patient Rooms versus Multiple Occupancy Rooms in Acute Care Environments.* US: Coalition for Health Environments Research, pp. 1-53. [online]
Available at:
https://www.healthdesign.org/sites/default/files/use_of_single_patient_rooms_v_multiple_occ._rooms-acute_care.pdf [Accessed 1 Dec. 2015].

Chaudhury, H., Mahmood, A., and Valente, M. (2009). *The Effect of Environmental Design on Reducing Nursing Errors and Increasing Efficiency in Acute Care Settings a Review and Analysis of the Literature.* Environment and Behavior 41 (6): pp. 755 – 786.

Chakrabarti, A. (2001) Sharing in Design – Categories, Importance, and Issues. In: *International Conference on Engineering Design*. ICED 01 Glasgow [online] Available at: http://www.cpdm.iisc.ernet.in/ideaslab/paper_scans/UID_132.pdf [Accessed 15 Jan. 2016].

Chakrabarti, A. (2004) A New Approach to Structure Sharing. *Journal of Computing and Information Science in Engineering*. [online] Available at: http://computingengineering.asmedigitalcollection.asme.org/article.aspx?articleid=1399884 [Accessed 15 Jan. 2016].

Chakrabarti, A., Singh, V. (2007) A method for structure sharing to enhance resource effectiveness. In: *Journal of Engineering Design Vol. 18. No. 1*. pp. 73-91. India: Taylor & Francis [online] Available at: http://www.cpdm.iisc.ernet.in/ideaslab/paper_scans/UID_58.pdf [Accessed 10 Jan. 2016].

Chang, S., and Chen, C. (2005). *Effects of Music Therapy on Women's Physiologic Measures, Anxiety, and Satisfaction During Cesarean Delivery*. Research in Nursing and Health 28 (6): pp. 453 – 461.

Cheek, F. E., Maxwell, R., and Weisman, R. (1971). *Carpeting the Ward: An Exploratory Study in Environmental Psychiatry*. Mental Hygiene 55 (1): pp. 109 – 118.

Chlan, L. (2000). *Music Therapy as a Nursing Intervention for Patients Supported by Mechanical Ventilation*. AACN Clinical Issues Advanced Practice in Acute Critical Care 11 (1): pp. 128 – 138.

Clay, R. A. (2001). *Green is Good for You*. Monitor on Psychology 32 (4): pp. 40 – 42.

Cooke, M., Chaboyer, W., and Hiratos, M. A. (2005). Music and its Effect on Anxiety in Short Waiting Periods: A Critical Appraisal. *Journal of Clinical Nursing* 14 (2): pp. 145 – 155.

Counsell, S. R., Holder, C. M., Liebenauer, L. L., Palmer, R. M., Fortinsky, R. H., Kresevic, D. M., Quinn, L. M., Allen, K. R., Covinsky, K. E., and Landefeld, C. S. (2000). Effects of a Multicomponent Intervention on Functional Outcomes and Process of Care in Hospitalized Older Patients: A Randomized Controlled Trial of Acute Care for Elders (ACE) in a Community Hospital. *Journal of the American Geriatrics Society* 48 (12): pp. 1572 – 1581.

Dalke, H., Little, J., Neimann, E., Camgoz, N., Steadman, G., Hill, S., and Stott, L. (2006). *Colour and Lighting in Hospital Design*. Optics and laser technology 38 (4 – 6): pp. 343 – 365.

de Dear, R. (2011). *Revisiting an Old Hypothesis of Human Thermal Perception: Alliesthesia*. In: Building Research and Information 39 (2): pp. 108 – 117.

Devlin, A. S., and Arneill, A. B. (2003). *Health Care Environments and Patient Outcomes: A Review of the Literature.* Environment and Behavior 35 (5): pp. 665 – 694.

Dijkstra, K., Pieterse, M. E., and Pruyn, A. (2008). *Stress-Reducing Effects of Indoor Plants in the Built Healthcare Environment: The Mediating Role of Perceived Attractiveness.* Preventive Medicine 47 (3): pp. 279 – 283.

Douglas, C. H., and Douglas, M. R. (2004). *Patient-Friendly Hospital Environments: Exploring the Patients' Perspective.* Health Expectations 7 (1): pp. 61 – 73.

Eames, I., Shoabi, D., Klettner, C. A., and Taban, V. (2009). Movement of Airborne Contaminants in a Hospital Isolation Room. *Journal of the Royal Society Interface* 6: 757 – 766. [Accessed August 20, 2012].

Eckmanns, T., Ruden, H., and Gastmeier, P. (2006). The Influence of High-Efficiency Particulate Air Filtration on Mortality and Fungal Infection Among Highly Immunosuppressed Patients: A Systematic Review. *Journal of Infectious Diseases* 193 (10): pp. 1408 – 1418.

Edwards, L., and Torcellini, P. (2002). *A Literature Review of the Effects of Natural Light on Building Occupants.* Technical report, Colorado National Renewable Energy Laboratory. [online] Available at: http://www.osti.gov/bridge [Accessed August 5, 2012].

Eder, W.E. (2008) Theory of Technical Systems and Engineering Design Science – Legacy of Vladimir Hubka. In: *International Design Conference*. Dubrovnik: Design Theory and Research Methodology. pp. 19-30. [online] Available at: https://www.designsociety.org/publication/26651/theory_of_technical_systems_and_engineering_design_science-legacy_of_vladimir_hubka [Accessed 30 Nov. 2015].

European Hospital and Healthcare Federation (HOPE), 2014. Hospitals in the 27 Member States of the European Union [online] Available at: http://www.hope.be/05eventsandpublications/docpublications/79_hospitals_in_eu/79-hospitals-in-the-eu-2009.pdf [Accessed 18 Mar, 2016].

European Hospital and Healthcare Federation (HOPE), 2014. Hospitals of the Future [online] Available at: http://www.hope.be/05eventsandpublications/docpublications/100_hospitals_2020/100_HOPE_Hospitals_2020_complete_September_2015.pdf [Accessed 20 Mar, 2016].

Evans, G. W., and Cohen, S. (1987). *Environmental Stress*. In: Handbook of Environmental Psychology, edited by D. Stokols and I. Altman, 571 – 610. New York: John Wiley.

Fairhall, K. V., Bache, L. and Dodd, P. (2015). *Patient Safety: Single-bed versus multi-bed hospital rooms.* [online] Available at: http://www.worldhealthdesign.com/Patient-Safety-Single-Bed-Versus-Multi-Bed-Hospital-Rooms.aspx [Accessed 14 Nov. 2015].

Fehrman, K. R., and Fehrman. C. (2004). *Color: The Secret Influence*. Upper Saddle River, N.J: Prentice Hall.

FGI (2010). *Guidelines for Design and Construction of Healthcare Facilities*. Chicago, IL: The Facility Guidelines Institute (FGI), 29.

FGI (2012). *Facility Guidelines Institute (FGI)*. [online] Available at: http://www.fgiguidelines.org

Fisk, W. J. (2001). *Estimates of Potential Nationwide Productivity and Health Benefits from Better Indoor Environments: An Update.* Chapter 4. In Indoor Air Quality Handbook, edited by Spengler, J. D., Samet, J. F., and Mccarthy, J. 1488 pp. New York: McGraw-Hill.

Flynn, E. A., Barker, K. N., Gibson, J. T., Pearson, R. E., Berger, B. A. and Smith, L. A. (1999). Impact of Interruptions and Distractions on Dispensing Errors in an Ambulatory Care Pharmacy. *American Journal of Health Systems Pharmacy* 56 (13): pp. 1319 – 1325.

Gero, J. S. (2006) *Design Prototypes: a Knowledge Representation Schema for Design.* Sydney: Association for the Advancement of Artificial Intelligence [online] Available at: http://www.aaai.org/ojs/index.php/aimagazine/article/view/854 [Accessed 10 Oct. 2015].

Glod, C. A., Teicher, M. H., Butler, M., Savino, M., Harper, D., Magnus, E., and Pahlavan, K. (1994). Modifying Quiet Room Design Enhances Calming of Children and Adolescents. *Journal of the American Academy of Child and Adolescent Psychiatry* 33 (4): pp. 558 – 566.

Goetz, P., Malone, E., Harmsen, C., Reno, K., Edelstein, E., Hamilton, D. K., Salvatore, A., Mann-Dooks, J., Oland, C. and Nanda, U. (2010). *An Introduction to Evidence-Based Design: Exploring Health and Design*. 2nd ed. Concord, CA: The Center for Health Design.

Goodall, D., and Etters, L. (2005). *The Therapeutic Use of Music on Agitated Behavior in Those with Dementia*. Holistic Nursing Practice 19 (6): pp. 258 – 262.

Gravesen, S., Larsen, L., Gyntelberg, F., and Skov, P. (1986). *Demonstration of Microorganisms and Dust in Schools and Offices*. Allergy 41 (7): pp. 520 – 525.

Grumet, G. (1993). *Pandemonium in the Modern Hospital*. The New England Journal of Medicine (NEJM) 328: pp. 433 – 437.

Hagerman, I., Rasmanis, G., Blomkvist, V., Ulrich, R. S., Eriksen, C. A., and Theorell, T. (2005). Influence of Coronary Intensive Care Acoustics on the Quality of Care and Physiological States of Patients. *International Journal of Cardiology* 98: pp. 267 – 270.

Hahn, T., Cummings, K. M., Michalek, A. M., Lipman, B. J., Segal, B. H., and McCarthy, P. L. (2002). *Efficacy of High-Efficiency Particulate Air Filtration in Preventing Aspergillosis in Immunocompromised Patients with Hematologic Malignancies.* Infection Control and Hospital Epidemiology 23 (9): pp. 525 – 531.

Harale, K. B. (2010). *The Role of Design in Communication, Interaction And Teamwork.*, Dissertation. The Degree of Master of Science, Cornell University, The Faculty of the Graduate School. [online] Available at: http://iwsp.human.cornell.edu/file_uploads/Harale_Ketki.pdf [Accessed April 28, 2012].

Harris, D. (2000). *Environmental Quality and Healing Environments: A Study of Flooring Materials in a Healthcare Telemetry Unit*. Dissertation. Department of Architecture, Texas A&M University, College Station, TX, Dissertation Abstracts International, 4202(00), DAI-A61/11 (University Digital no. AAT 9994253).

Harvard Business Review (2015) *A Vision for Hospital at Home Programs* [online] Available at: https://hbr.org/2015/12/a-vision-for-hospital-at-home-programs [Accessed 10 Mar, 2016].

Hathorn, K., and Nanda, U. (2008). *A Guide to Evidence-Based Art.* Concord, California: The Center for Health Design, 235. [online] Available at: http://www.healthdesign.org/sites/default/files/Hathorn_Nanda_Mar08.pdf [Accessed September 1, 2012].

Hendrich, A. (2004) In: *Keeping Patients Safe: Transforming the Work Environment of Nurses,* Quality Chasm Series, Institute of Medicine

Hendrich, A. L, Fay, J. and Sorrells, A. K. (2004) Effects of acuity-adaptable rooms on flow of patients and delivery of care. In: *American Journal of Critical Care*, 13(1), pp. 35–45.

Hicks, B.J., Culley, S.J. and Mullineux, G. (2002) Cost estimation for standard components and systems in the early phases of the design process. *Journal of Engineering Design. Vol.13 No.4* pp.272-292 [online] Available at: http://www.tandfonline.com/loi/cjen20 [Accessed 10 Feb. 2016].

Hilton, B. A. (1985). *Noise in Acute Patient Care Areas*. Research in Nursing and Health 8 (3): pp. 283 –291.

Hölmström, J. (2015) *The direct digital manufacturing (r)evolution: An empirical perspective on its adoption and competitiveness.* Manuscript: Aalto University

Horton, J. G. (1997). *Lighting*. New York, NY: John Wiley & Sons, Inc.

Johnson, A. N. (2001). Neonatal Response to Control of Noise Inside the Incubator. Pediatric Nursing 27 (6): pp. 600 – 605.

Johnson, B. H., and Abraham, M. R. (2004). *Designing the Neonatal Intensive Care Unit for Optimal Family Involvement.* Clinics in Perinatology 31 (2): pp. 353 – 382.

Joseph, A. (2006). *The Impact of Light on Outcomes in Healthcare Settings.* Concord, CA: The Center for Health Design. [online] Available at: http://www.healthdesign.org/chd/research/impact-light-outcomes-healthcare-settings [Accessed June 17, 2012].

Joseph, A. (2006). *The Impact of the Environment on Infections in Healthcare Facilities*. Vol. Issue Paper #1. Concord, CA: The Center for Health Design, 19. [online] Available at: http://www.healthdesign.org/sites/default/files/Impact%20of%20the%20Environment%20on%20Infections%20in%20HC%20Facilities_0.pdf [Accessed July 13, 2012].

Joseph, A. (2006*). The Role of the Physical and Social Environment in Promoting Health, Safety, and Effectiveness in the Healthcare Workplace*. The Center for Health Design. [online] Available at:

https://www.healthdesign.org/chd/knowledge-repository/role-physical-and-social-environment-promoting-health-safety-and-effectiven [Accessed Apr 21, 2016].

Joseph, A. (2007). *Hospitals That Heal. Hospital Design for the 21st Century*. Asian Hospital and Healthcare Management 13: pp. 11 – 13. [online] Available at: http://www.asianhhm.com/newsletter/images/ahhm_issue13.pdf [Accessed September 25, 2012].

Joseph, A., and Ulrich, R. (2007). *Sound Control for Improved Outcomes in Healthcare Settings*. Concord, CA: The Center for Health Design, 17. [online] Available at: http://www.healthdesign.org/sites/default/files/Sound%20Control.pdf [Accessed April 20, 2016].

Kaplan, R. (1992). *The Psychological Benefits of Nearby Nature*. In Role of Horticulture in Human Well-being and Social Development: A National Symposium, edited by Relf, D., pp. 125 – 133. Arlington, Virginia: Timber Press.

Keates, S., Clarkson, P. J., Harrison, L. and Robinson, P. (2000*) Towards a Practical Inclusive Design Approach.* Cambridge: ACM2000 [online] Available at: http://web.mit.edu/16.459/Keates.pdf [Accessed 15 Sept. 2015].

Keep, P. J., James, J., and Inman, M. (1980). *Windows in the Intensive Therapy Unit.* Anesthesia 35 (3): pp. 257 – 262.

Kutash, M., and Northrop, L. (2007). Family Members' Experiences of the Intensive Care Unit Waiting Room. *Journal of Advanced Nursing* 60 (4): pp. 384 – 388.

Lai, H., Chen, C., Peng, T., Chang, F., Hsieh, M., Huang, H., and Chang, S. (2006). Randomized Controlled Trial of Music During Kangaroo Care on Maternal State Anxiety and Preterm Infants' Responses. *International Journal of Nursing Studies* 43 (2): pp. 139 – 146.

Lankford, M. G., Collins, S., Youngberg, L., Rooney, D. M., Warren, J. R., and Noskin, G. A. (2006). Assessment of Materials Commonly Utilized in Healthcare: Implications for Bacterial Survival and Transmission. *American Journal of Infection Control* 34 (5): pp. 258 – 263.

Larson, E. (1999). *Skin Hygiene and Infection Prevention: More of the Same or Different Approaches?.* Clinical Infectious Disease 29 (5): pp. 1287 – 1294.

Lawson, B. and Phiri, M. (2003).*The architectural environment and its effects on patient health outcomes*. TSO for NHS Estates, London.

Lee, O., Chung, Y., Chan, M. F., and Chan, W. M. (2005). Music and its Effect on the Physiological Responses and Anxiety Level of Patients Receiving Mechanical Ventilation: A Pilot Study. *Journal of Clinical Nursing* 14 (5): pp. 609 – 620.

Leese, K. E., Cole, E. C., Hall, R. M., and Berry, M. A. (1997). Measurement of Airborne and Floor Dusts in a Nonproblem Building. *American Industrial Hygiene Association Journal* 58 (6): pp. 432 – 438.

Lewis, N. (2012). Remote Patient Monitoring Market To Double By 2016. [online] InformationWeek Available at: http://www.informationweek.com/mobile/remote-patient-monitoring-market-to-double-by-2016/d/d-id/1105484 [Accessed 30 Oct. 2015].

Li, Y., Leung, G. M. , Tang, J. W., Yang, X., Chao, C. Y., Lin, J. Z., Lu, J. W. et al. (2007). *Role of Ventilation in Airborne Transmission of Infectious Agents in the Built Environment – A Multi-Disciplinary Systematic Review*. Indoor Air 17: pp. 2 – 18.

Lindbeck, J.R. and Wygant, R.M. (1995) *Product Design and Manufacture*. Englewood Chiffes: NJ.

Lorenz, S. G. (2007). The Potential of the Patient Room to Promote Healing and Well-Being in Patients and Nurses: an Integrative Review of the Research. Holistic Nursing Practice 21 (5): pp. 263 – 277.

Lundstrom, T., Pugliese, G., Bartley, J., Cox, J., Guither, C., Michigan, D., and Illinois, O. (2002). Organizational and Environmental Factors that Affect Worker Health and Safety and Patient Outcomes. *American Journal of Infection Control* 30 (2): pp. 93 – 106.

Mackworth, N. H. (1950). *Researches on the Measurement of Human Performance*. London: Medical Research Council. H Majesty’s Stationery Office.

MAD (2015), ArchiLogs [online] Available at: http://mad.fi/tuotteet/muut/archilogs [Accessed 25 Dec, 2015].

Maier, J.R.A. and Fadel, G.M. (2001). *Affordance: the fundamental concept in engineering design*. In: Proceedings of ASME Design Theory and Methodology Conference, Pittsburgh, PA. Paper no. DETC2001/DTM-21700.

Maier, J.R.A. and Fadel, G.M. (2002). *Comparing function and affordance as bases for design*. In: Proceedings of ASME Design Theory and Methodology Conference, Montreal, Canada. Paper no. DETC2002/DTM-34029.

Malone, E. B., and Dellinger, B. A. (2011). *Furniture Design Features and Healthcare Outcomes*. Concord, California: The Center for Health Design, 73. [online] Available at: http://www.healthdesign.org/sites/default/files/FurnitureOutcomes_2011.pdf [Accessed August 18, 2012].

Martin, M.V., Ishii, K. (2002) Design for variety: developing standardized and modularized product platform architectures. In: *Research in Engineering Design 13*. pp. 213-235. [online] Available at: http://web.mit.edu/deweck/Public/ESD39/Readings/GVImetrics.Martin-Ishii-2002.pdf [Accessed 10 Dec. 2015].

Martin, R. and Ng, F. (2014). *Hospital bed room configurations: private, semi-private or shared?* [online] TAHPI Available at: http://www.healthdesign.com.au/tahpi-test/pdf/resources_1.pdf [Accessed 22 Oct. 2015].

McCaffrey, R., and Locsin, R. (2004). The Effect of Music Listening on Acute Confusion and Delirium in Elders Undergoing Elective Hip and Knee Surgery. *International Journal of Older People Nursing* 13 (6b): pp. 91 – 96.

McCann, S., Byrne, J. L., Rovira, M., Shaw, P., Ribaud, P., Sica, S., Volin, L. et al. (2004). *Outbreaks of Infectious Diseases in Stem Cell Transplant Units: A Silent Cause of Death for Patients and Transplant Programs.* Bone Marrow Transplant 33 (5): pp. 519 – 529.

Menegazzi, J. J., Paris, P., Kersteen, C., Flynn, B., and Trautman, D. E. (1991). *A Randomized Controlled Trial of the Use of Music During Laceration Repair.* Annals of Emergency Medicine 20 (4): pp. 348 – 350.

Miller, T., Elgård, P. (1998) Defining Modules, Modularity and Modularization Evolution of the Concept in a Historical Perspective. In: *Design for Integration in Manufacturing Proceedings of the 13th IPS Research Seminar*. Fuglsoe: Aalborg University. [online] Available at: http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.454.868 [Accessed 7 Nov. 2015].

Nevala, N., and Tamminen-Peter, L. (2004). Ergonomics and Usability of an Electrically Adjustable Shower Trolley. *International Journal of Industrial Ergonomics* 34: pp. 131 – 138.

NCSU. (2015) *Introduction to Universal Design*. [online] Available at: http://www.ncsu.edu/project/design-projects/sites/cud/content/UD_intro.html [Accessed 20 Sept. 2015].

Okamoto-Mizuno, K., Tsuzuki, K. and Mizuno, K. (2004). Effects of Mild Heat Exposure on Sleep Stages and Body Temperature in Older Men. *International Journal of Biometeorology* 49 (1): pp. 32 – 36.

Olsberg, D. (2005). *Ageing in Place: Feeling Safe and Secure at home to age in place.* [online] Report Available at: http://www.ahuri.edu.au/research/final-reports/88 [Accessed 20 Oct. 2015].

Ölvander, J. (2005) Robustness considerations in multi-objective optimal design. *Journal of Engineering Design. Vol. 16 No. 5.* Pp.511-523. [online] Available at: http://www.tandfonline.com/doi/abs/10.1080/09544820500287300 [Accessed 11 Feb. 2016].

Pahl, G. and Beitz, W. (1996) *Engineering Design, A systematic approach*. Springer: London.

Parker, D. L., and Hodge, J. R. (1976). Delirium in a Coronary Unit. *Journal of the American Medical Association (JAMA)* 201: pp. 132 – 133.

Parmeggiani, P. L. (1987). *Interaction Between Sleep and Thermoregulation: An Aspect of the Control of Behavioural States.* Sleep 10: pp. 426 – 435.

Parsons, R. (1991). The Potential Influences of Environmental Perception on Human Health. *Journal of Environmental Psychology* 11: pp. 1 – 23.

Peppin, R. J. (1997). *The ASHRAE Handbook on Noise and Vibration: A Critical Review*. The Journal of the Acoustical Society of America 101 (5): 3036. [online] Available at: http://asadl.org/jasa/resource/1/jasman/v101/i5/p3036_s1 [Accessed 12 Dec, 2015].

Press Ganey US national data (2002) [online] Available at: http://www.pressganey.com/resources [Accessed 1 May, 2002].

Qian, J., and Ferro, A. R. (2007). *Characterization of the particle resuspension source from human activity* [abstract]. Healthy air—better work, 29 – 31 May 2007. Helsinki, Finnish Institute of Occupational Health, 51.

Ramsey, J., and Kwon, Y. (1988). *Simplified decision rules for predicting performance loss in the heat.* In Proceedings of Proceedings, Seminar on Heat Stress Indices, pp. 337 – 371.

Reiling, J. G., Knutzen, B. L., Wallen, T. K., McCullough, S., Miller, R., and Chernos, S. (2004). *Enhancing the Traditional Hospital Design Process: A Focus on Patient Safety*. Joint Commission Journal on Quality and Safety 30 (3): pp. 115 – 124.

RemPods (2014), Reminiscence Pods [online] Available at: http://www.rempods.co.uk [Accessed 15 Feb, 2016].

Robbins, C. L. (1986). *Daylighting Design and Analysis*. New York: Van Nostrand Reinhold Company.

Särkämö, T., and Soto, D. (2012). *Music Listening After Stroke: Beneficial Effects and Potential Neural Mechanisms.* Annals of the New York Academy of Sciences 1252 (April): pp. 266 – 281.

Salonen, H., Lahtinen, M., Lappalainen, S., Nevala, N., Knibbs, L. D., Morawska, L. and Reijula, K. (2012). *Physical Characteristics of the Indoor Environment that Affect Health and Wellbeing in Healthcare Facilities: A Review*. Intelligent Buildings International.

Sehulster, L., Chinn, R. Y., Arduino, M. J., Carpenter, J., Donlan, R., Ashford, D., Besser, R. et al. (2004). *Guidelines for Environmental Infection Control in Health-Care Facilities. Recommendations of CDC and the Healthcare Infection Control Practices Advisory Committee (HICPAC)*. Chicago, IL: American Society for Healthcare Engineering/American Hospital Association.

Singer, D.J., Doerry, C.N. and Buckley, M.E. (2008) *What is Set-Based Design?* [online] Available at: http://www.doerry.org/norbert/papers/SBDFinal.pdf [Accessed 13 Dec. 2015]

Singh, V. and Gu, N. (2011) *Towards an integrated generative design framework.* Deakin University and University of Newcastle: Elsevier Ltd. [online] Available at http:// www.elsevier.com/locate/destud [Accessed 1 Jan. 2016].

Skoutelis, A. T., Westenfelder, G. O., Beckerdite, M., and Phair, J. P. (1994). Hospital Carpeting and Epidemiology of Clostridium Difficile. *American Journal of Infection Control* 22 (4): pp. 212 – 217.

Slevin, M., Farrington, N., Duffy, G., Daly, L. and Murphy, J. F. (2000). *Altering the NICU and Measuring Infants' Responses*. Acta Paediatrica 89 (5): pp. 577 – 581.

Solet, J. M., Buxton, O. M., Ellenbogen, J. M., Wang, W., and Carballiera, A. (2010). *Evidence-Based Design Meets Evidence-Based Medicine: The Sound Sleep Study.* Concord, CA: The Center for Health Design. [online] Available at: http://www.healthdesign.org/sites/default/files/Validating%20Acoustic%20Guidelines%20for%20HC%20Facilities_Sound%20Sleep%20Study.pdf [Accessed 7 Dec, 2015].

Springer, T. (2007). *Ergonomics for Healthcare Environments*. Knoll: HERO, Inc.

Standley, J. M. (1986). Music Research in Medical/Dental Treatment: Meta-Analysis and Clinical Applications. *Journal of Music Therapy* XXII: pp. 56 – 122.

Stichler, J. (2001). *Creating Healing Environments in Critical Care Units*. Critical Care Nursing Quarterly 24 (3): pp. 1 – 20.

Suh, N.P. (1995) Designing-in of Quality through Axiomatic Design. *IEEE Transactions on Reliability. Vol. 44. No. 2*. Pp.256-264. [online] Available at: https://dspace.mit.edu/bitstream/handle/1721.1/25610/Suh-1995-Designing-in.pdf?sequence=1 [Accessed 7 Feb. 2016].

Tang, J., Li, Y., Eames, I., Chan, P., and Ridgway, G. (2006). Factors Involved in the Aerosol Transmission of Infection and Control of Ventilation in Healthcare Premises. *Journal of Hospital Infection* 64 (2): pp. 100 – 114.

Taperi, J., Porter, M. E., Vuorenkoski, L. and Baron, J. F. (2009) *The Finnish Health Care System: A Value-Based Perspective.* Helsinki: Edita Prima Ltd., pp. 36-112.

Tekes, (2015). *Smart Solutions from Finland* [online] Available at: http://www.tekes.fi/en [Accessed 10 Dec. 2015].

Thatcher, T. L., and Layton, D. W. (1995). *Deposition, Resuspension and Penetration of Particles within a Residence.* Atmospheric Environment 29 (13): pp. 1487 – 1497.

Tofle, R. B., Schwarz, B., Yoon, S.Y. and Max-Royale, A. (2004). *Color in Healthcare Environments (Monograph on a CD)*. Concord, California: Coalition for Health Environments Research (CHER). [online] Available at: http://www.healthdesign.org/sites/default/files/color_in_hc_environ.pdf [Accessed February 20, 2012].

Tunga, Y. C., Hu, S. C., Tsaia, T.-I., and Changa, I.-L. (2009). *An Experimental Study on Ventilation Efficiency of Isolation Room.* Building and Environment 44 (2): pp. 271 – 279.

Tyson, G. A., Lambert, G., and Beattie, L. (2002). The Impact of Ward Design on the Behaviour, Occupational Satisfaction and Well-Being of Psychiatric Nurses. *International Journal of Mental Health Nursing* 11 (2): pp. 94 – 102.

Ulrich, K.T. (1988) *Computation and pre-parametric design.* PhD thesis: AI Laboratory, Massachusetts Institute of Technology, Cambridge, MA.

Ulrich, K.T. and Eppinger, S.D. (1995) *Product Design and Development*. New York: McGraw Hill.

Ulrich, R. S. (1991). Effects of Health Facility Interior Design on Wellness: Theory and Recent Scientific Research. *Journal of Health Care Design* 3: pp. 97 – 109.

Ulrich, R. S. (1999). *Effects of Gardens on Health Outcomes: Theory and Research*. In Healing Gardens: Therapeutic Benefits and Design Recommendations, edited by M. Cooper and M. Barnes, pp. 27 – 86. New York: John Wiley.

Ulrich, R. S. (2000). Effects of healthcare environmental design on medical outcomes. In: *Design & Health– The Therapeutic Benefits of Design*. 2nd International Congress on Design and Health, Karolinska Institute Stockholm, Sweden, 49 – 59.

Ulrich, R. S. (2000). *Environmental Research and Critical Care.* In: ICU 2010: Design for the Future, edited by D. K. Hamilton, 195 – 207. Center for Innovation in Health Facilities: Houston.

Ulrich, R. S. (2000). *Evidence based environmental design for improving medical outcomes.* In Proceedings of the Conference, Healing By Design: Building for Health Care in the 21st Century, 3.1 – 3.10. Montreal: McGill University Health Centre.

Ulrich, R. S. and Zimring, C. (with Quan, Joseph, and Choudhary) (2004). *The Role of the Physical Environment in the Hospital of the 21st Century.* The Center for Health Design and the Robert Wood Johnson Foundation.

Ulrich, R., and Gilpin, L. (2003). *Healing Arts – Nutrition for the Soul*. Putting Patients First – Designing and Practicing Patient-Centered Care, edited by P. M. Charmel, S. B. Frampton and L. Gilpin, pp. 117 –146. San Francisco: Jossey-Bass.

Ulrich, R. (2006). Effects of Single Versus Multi-Bed Rooms on Outcomes. *Welsh Health Estates and IHEEM Conference.* [online] pp. 1-53. Available at: www.wales.nhs.uk/sites3/documents/254/ulrichday1.pdf [Accessed 9 Nov. 2015].

Ulrich, R., and Barach, P. (2006). *Designing Safe Healthcare Facilities – What are the data and where do we go from here?.* Paper presented at the Healthcare Environments Research Summit 2006. Atlanta, GA.

Ulrich, R. S., Zimring, C., Zhu, X., CuBose, J., Seo, H. B., Choi, Y. S., Quan, X., and Joseph, A. (2008). *A Review of the Research Literature on Evidence Based Healthcare Design.* Health Environments Research & Design Journal 1 (3): pp. 61 – 125.

USAGE (1997). *Design Guide for Interiors*. Washington, DC: U.S. Army Corps Engineers, 196. [online] Available at: http://wbdg.org/ccb/ARMYCOE/COEDG/dg_1110_3_122.pdf [Accessed 10 Feb, 2016].

van den Berg, A. E., Hartig, T., and Staats, H. (2007). Preference for Nature in Urbanized Societies: Stress, Restoration, and the Pursuit of Sustainability. *Journal of Social* Issues 63 (1): pp. 79 – 96.

Van Enk, R. A. (2004). *The Effect of Single Versus Two-Bed Rooms on Hospital-Acquired Infection Rates.* [online] healthdesign.org Available at: https://www.healthdesign.org/chd/knowledge-repository/use-single-patient-rooms-versus-multiple-occupancy-rooms-acute-care-environ [Accessed 20 Oct. 2015].

Vos, L., S. Groothuis, and van Merode, G. G. (2007). *Evaluating Hospital Design from an Operation Management Perspective.* Health Care Management Science 10, pp. 357 – 364.

Walch, J. M., Rabin, B. S., Day, R., Williams, J. N., Choi, K., and Kang, J. D. (2005). *The Effect of Sunlight on Postoperative Analgesic Medication Use: A Prospective Study of Patients Undergoing Spinal Surgery*. Psychosomatic Medicine 67 (1): pp. 156 – 163.

Warwick Manufacturing Group. (2013) *Product Excellence using Six Sigma – Quality Function Deployment.* Coventry: University of Warwick [online] Available at: http://www2.warwick.ac.uk/fac/sci/wmg/ftmsc/modules/modulelist/peuss/slides/section_6a_qfd_notes.pdf [Accessed 15 Sept. 2015].

Welch, R. V. and Dixon, J. R. (1994) Guiding Conceptual Design Through Behavioral Reasoning. *Resource Engineering Design. Vol.6. No.3*. pp.169 – 188 [online] Available at: http://diyhpl.us/~bryan/papers2/Guiding%20conceptual%20design%20through%20behavioral%20reasoning%20-%20Welch%20-%20Dixon%20-%201994.pdf [Accessed 30 Mar. 2016].

WHO (2007) *Epidemic-Prone & Pandemic-Prone Acute Respiratory Diseases*. *Infection Prevention & Control in Health-Care Facilities*. Geneva: World Health Organization. [online] Available at: http://influenzatraining.org/documents/s16092e/s16092e.pdf [Accessed May 10, 2012].

WHO (2007). *Noise, Regulations Guidelines for Community Noise*. Geneva: World Health Organization.

WHO (2009). *WHO Guidelines on Hand Hygiene in Health Care. First Global Patient Safety Challenge Clean Care is Safer Care*. Geneva, Switzerland: World Health Organization, 270. [online] Available at: http://whqlibdoc.who.int/publications/2009/9789241597906_eng.pdf. [Accessed September 5, 2013].

WHO (2009). *WHO Publication/Guideline 2009. Natural Ventilation for Infection Control in Health-Care Settings*. Geneva: World Health Organization.

Wiles, J. L., Leibing, A., Guberman, N., Reeve, J. and Allen, R. (2011) The Meaning of "Ageing in Place" to Older People. *The Gerontologist Journal* [online] pp. 1-10 Available at: http://gerontologist.oxfordjournals.org/content/52/3/357.full [Accessed 15 Dec. 2015].

Willmott, M. (1986). *The Effect of a Vinyl Floor Surface and a Carpeted Floor Surface Upon Walking in Elderly Hospital In-Patients*. Age Ageing 15 (2): pp. 119 – 120.

Wilson, L. M. (1972). *Intensive Care Delirium: The Effect of Outside Deprivation in a Windowless Unit*. Archives of Internal Medicine 130 (2): pp. 225 – 226.

Withington, S., Chambers, S. T., Beard, M. E., Inder, A., Allen, J. R., Ikram, R. B., Schousboe, M. I., Heaton, D. C., Spearing, R. I., and Hart, D. N. (1998). Invasive Aspergillosis in Severely Neutropenic Patients

Over 18 Years: Impact of Intranasal Amphotericin B and HEPA Filtration. *Journal of Hospital Infection* 38 (1): pp. 11 – 18.

Wu, Z. (2011). *Evaluation of A Sustainable Hospital Design Based on Its Social and Environmental Outcomes*. Dissertation. A Thesis Presented to the Faculty of the Graduate School of Cornell University In Partial Fulfillment of the Requirements for the Degree of Master of Science, Cornell University.

Wynn, D.C. (2007) *Model-Based Approaches to Support Process Improvement in Complex Product Development.* PhD. University of Cambridge.

Yang, K., Hongwei, Z. (2000) A Comparison of TRIZ and Axiomatic Design. In: *First International Conference on Axiomatic Design*. Cambridge: ICAD56. Pp.235-243. [online] Available at: http://ns.dfss-software.com/technology/icad/icad2000/icad2000_056.pdf [Accessed 8 Feb. 2016].

Yinnon, A. M., Ilan, Y., Tadmor, B., Altarescu, G., and Hershko, C. (1992). Quality of Sleep in the Medical Department. *British Journal of Clinical Pharmacology (BJCP)* 46 (2): pp. 88 – 91.

Zhao, B., Yang, C. Q., Chen, C., Chao, F., Xu, D. Y., Sun, L. C., Wei, G. and Li, Y. (2009). *How Many Airborne Particles Emitted From a Nurse Will Reach the Breathing Zone/Body Surface of the Patient in ISO Class-5 Single- Bed Hospital Protective Environments? A Numerical Analysis*. Aerosol Science and Technology 43 (10): pp. 990 – 1005.

Zun, L. S., and Downey, L. V. (2005). The Effect of Noise in the Emergency Department. Academic Emergency Medicine 42 (7): pp. 663 – 666.